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Rhamnus prinoides-based Agroforestry for Climate-Smart Agriculture in Drylands of Tigray, Ethiopia

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Declaration

I declare that this dissertation is the outcome of my own research work and has not been submitted before as part of the requirements any for other degree program elsewhere. All references to other materials have been duly acknowledged.

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Subject: Approval of a Dissertation for a Review

Destaalem Gebremeskel, a Prospective PhD Candidate, in the PhD Program in Climate Change and Rural Development, has been working on his Dissertation on the topic "***Rhamnus prinoides*-based Agroforestry for Climate-Smart Agriculture in Drylands of Tigray, Ethiopia**", under our supervision. Destaalem Gebremeskel has finalized his research work and dissertation write-up to our satisfaction. Hence, we unanimously approve his dissertation for review and examination per the University regulations. Four printed copies of the dissertation and a soft copy are submitted herewith.

With kind regards,

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Destaalem Gebremeskel

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List of Abbreviations

AESC	Agro-ecological Suitability Classes
AFS	Agroforestry Systems
AGB	Aboveground Biomass
AUC	Area Under the Curve
BCR	Benefit Cost Ratio
BD	Bulk Density
BGB	Belowground Biomass
BoARD	Bureau of Agriculture and Rural Development
C	Carbon
CD	Crown Diameter
CH_4	Methane
CO_2	Carbon di Oxide
CSA	Central Statistics Agency
DEM	Digital Elevation Model
DNR	Discounted Net Return
DSH	Diameter at Stump Height
EAI	Equalized Annual Income
EC	Electrical Conductivity
FAO	Food and Agriculture Organization
GHGs	Green House Gases
glm	general linear model
GPS	Global Position System
ha	hectare
Ht	Height
IPCC	International Panel of Committee for Climate
K	Potassium
Kg	Kilogram
lm	Linear model
m	meter
MaxEnt	Maximum Entropy
MC	Moisture Content
Mg	Mega gram
MPE	Mean of Predicted Error
Mt	Metric tone
N	Nitrogen
N2O	Nitrogen die Oxide
NPV	Net Present Value
OC	Organic Carbon
P	Phosphorus
ROC	Receiver Operating Characteristics
SOC	Soil Organic Carbon
SSP	Socioeconomic Pathways
USD	United States Dollar

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Abstract

Agriculture is the backbone of socioeconomic development in many developing countries, but climate variability and land degradation are threatening productivity and income. Adopting climate-smart agricultural practices has been increasingly suggested as a solution. Locally practiced tree-based farming systems, such as agroforestry, can offer a promising solution, helping farmers boost productivity, adapt to climate change, and sequester carbon. However, the role and potential of agroforestry practices depend on many socioeconomic and biophysical factors, suggesting for the need of context-specific study. Integrating *R. prinoides* trees/shrubs with crops is local or indigenous practice in Tigray, Ethiopia providing multiple benefits. Thus, this PhD study aimed at assessing the distribution and characteristics, socioeconomic benefits, and adaptation and mitigation roles of *Rhamnus prinoides*-based agroforestry practice in four consecutive chapters.

Using Maxent model, the future distribution of *R. prinoides* agroforestry under climate change scenarios was predicted, showing that suitable areas may shrink. *R. prinoides* is successful in the highlands and midlands with moderate temperature, good soil, and partial sunlight. Field surveys of 191 households practicing *R. prinoides* agroforestry reveal that the system thrives in rain-fed areas and is particularly resilient due to its inverse phenology, which reduces competition with crops, and optimizes water use. *R. prinoides*-based agroforestry is not only more profitable than traditional wheat farming, yielding three times higher returns, but also creates additional employment and strengthens land use rights, with women playing a central role in harvesting and income management. The practice enhances farmers' resilience by diversifying production and stabilizing income throughout the year. Beyond social and economic benefits, *R. prinoides* agroforestry contributes significantly to climate change mitigation, with carbon stocks up to three times higher than in annual crop mono-cropping systems.

This research underscores the importance of context-specific agroforestry systems that align with both biophysical and socioeconomic factors. Scaling up *R. prinoides* agroforestry and similar practices can play a critical role in meeting global climate-smart agriculture goals, offering a sustainable path for smallholder farmers to thrive in the face of climate change. Incorporating tree-based farming into agricultural practices not only boosts productivity but also helps mitigate climate impacts, making it a key strategy for building resilient and sustainable agricultural systems worldwide.

Key Words: Adaptation, Diversification, Climate variability, Farming characteristics, Mitigation, Profitability, Species distribution, Specialization, Sustainable intensification.

Chapter 1 Introduction

1.1 Background and Justification

Developing countries heavily depend on agriculture for rural livelihoods and economic development. However, challenges such as population pressure, limited arable land, outdated farming practices, land degradation, fluctuating markets, and the impact of climate change have significantly hindered agricultural productivity and income (Mbow et al. 2014; Paul et al. 2017; Tian et al. 2021). These are threatening food security and exacerbate poverty in rural communities. Intensive agricultural systems have boosted productivity globally, but caused soil degradation, biodiversity loss, and environmental pollution, negatively impacting climate, food security, and farm incomes (Keating et al. 2010; Krausmann et al. 2013). Conventional agricultural practices such as annual crop mono-cropping in developing countries, contribute to land degradation, climate variability and change, and are significant sources of global greenhouse gas emissions (IPCC 2007; Schaffnit-Chatterjee 2011). Climate change impacts are slowing agricultural growth and hindering socioeconomic development (Wagesho et al. 2013; Dazé 2014; IPCC 2014), particularly in the drylands, which face harsh agroclimatic conditions, resource degradation, and moisture shortage (Sietz et al. 2011; Tewari et al. 2014). To address these challenges, sustainable farming solutions, including tree-based systems like agroforestry, are increasingly recognized as effective strategies for improving productivity, conserving resources, and enhancing resilience to climate shocks (Mbow et al. 2014; Paul et al. 2017; Tian et al. 2021).

Agriculture has a large potential to enhance productivity and adapt to and mitigate the effects of climate change through adopting climate-smart practices. Climate-smart agriculture (CSA) is an approach to achieving sustainable agriculture development (Lipper and Zilberman 2018; FAO 2018). Diversifying the production system to include significant tree components is a local strategy to improve rural livelihoods and buffer against production and income risks associated with climatic variability and change (Verchot et al. 2007). A diversified farming system that harbors agro-biodiversity and integrates trees/shrubs into land-use systems is important for the sustainable intensification of agricultural production through improved crop and land management (Mueller et al., 2012; Gockowski and Asten 2012; Garnett et al. 2013). Trees/shrubs provide a wide range of important products and services that people in the tropics want and need. Trees can play an important role in income generation and food and fuel security for resource-poor rural households while underpinning the sustainability of their farming systems (Cooper et al. 1996). The presence of trees on farms provided a more accessible, safe, and stable source of fuel wood for energy and income, particularly benefiting women (Thorlakson and Neufeldt 2011). Moreover, tree-based production systems often produce crops of higher value than raw (Verchot et al. 2007; Leakey 2012). Accordingly, agroforestry is suggested as a global solution to increase land-use efficiency, while reducing environmental impacts and economic risks for farmers (Paul et al. 2017).

Agroforestry is increasingly recognized in multifunctional agriculture, providing low-input, resource-conserving farming approaches that are socially relevant for rural development and relate well to production, livelihood, and ecosystem functions (Leakey 2012). Agroforestry requires low external inputs and has a high recycling rate (Koohafkan et al. 2012) that can be enhanced through better farming and improved tree and crop variety (Garrity 2004; Leakey 2012). Agroforestry can positively influence the drivers of sustainable intensification such as nutrient cycling and water use and regulation, and genetic diversity at plot and landscape levels (Carsan et al. 2014; Cardinale et al. 2011). The different species integrated in the practice support productivity at various times and increase farmland and labor use efficiency (Isbell et al. 2011; Paul et al. 2017). Well-designed and properly managed agroforestry systems could increase and sustain yield and income from limited land size (Lasco et al. 2014). Thus, agroforestry can be an option for smallholder farmers to increase productivity on limited land sizes to improve their livelihood.

Agroforestry practices are financially advantageous compared to the annual land use types (Duguma 2012). Developing safe economic routes that diversify marketable products and enhance business opportunities through targeted marketing strategies makes agroforestry systems profitable (Dawson et al. 2013; Leakey 2012). Financial profitability of agroforestry encourages the use of a sustainable land-use management practice to attain environmental and socioeconomic benefits (Alavalapati et al. 2004). Commercial agroforestry products incentivize subsistence farmers to plant trees/shrubs to reduce poverty and enhance food and nutritional security, human health, and environmental sustainability (Garrity 2004; Duffy et al. 2021). Hence, agroforestry development can play an important role in enhancing social coexistence and cultural maintenance of communities through creating employment opportunities and sustainable productivity (Leakey 2012; Dawson et al. 2013).

Agroforestry offers important opportunities for creating synergies between adaptation and mitigation actions (Verchot et al. 2007; Schoeneberger et al. 2012). Agroforestry enhances farmers' ability to adapt to climate change because of its multiple benefits including food provision, supplementary income, and environmental services (Lasco et al. 2014). Agroforestry systems that include significant trees/shrubs can be resilient to climate variability impacts because of their ability to maintain or modify their environment (van Noordwijk et al. 2021) and buffer against production and income risks (Verchot et al. 2007; Leakey 2012; Dawson et al. 2013). Agroforestry can play a crucial role in improving resilience to uncertain climates through microclimate buffering and regulation of water flow (Nguyen et al. 2013) and because of permanent tree/shrub cover and varied ecological niches (Smit 2006). Agroforestry systems provide greater stability through more diversified enterprises with different sources of income and products, providing a buffer against yield fluctuations caused by unstable climate or extreme weather events (Méndez et al. 2010; Cubbage et al. 2012). Agroforestry systems can play a significant role in mitigating climate change through emission reduction and increased CO_2 sequestration (Upson et al. 2016; Mbow et al. 2014; Aertsens et al. 2013; FAO 2010; Mosquera-Losada et al. 2008). The potential of agroforestry in carbon sequestration can be increased up to 90-150 tones C ha^{-1} $year^{-1}$ over a potential area of 900 million ha (Garrity 2004; Leakey 2010). Agroforestry systems have 3 to 4 times more biomass than conventional treeless agricultural systems with carbon stocks ranging from 29-228 Mg C $ha^{-1}year^{-1}$ (Matocha et al. 2012; Mbow et al. 2014). Agroforestry systems are more efficient in capturing the resources available at the site for biomass growth which may result in higher carbon inputs to the soil (Nair et al. 2010).

This study explores the role of tree-based farming systems, specifically *Rhamnus prinoides*-based agroforestry, in promoting climate-smart agriculture in the drylands of northern Ethiopia. *R. prinoides*, a shrub or small tree native to East, Central, and South Africa, is widely integrated into smallholder farming systems in this region. Known locally as "Gesho" and commonly called Dogwood, *R. prinoides* thrives in medium to high altitudes (1500–2500 m) and moist, humus-rich soils. It is valued for its role in soil conservation, erosion control, and as a natural windbreak. In the Tigray Region, particularly in Ahforom and Ganta-Afeshum districts, *R. prinoides* is commonly intercropped with various crops, serving both commercial and subsistence purposes, notably in the production of traditional local beverages like *Tella* and *Tej*. Beyond its economic uses, *R. prinoides* is also employed in traditional medicine. The integration of *R. prinoides* into farming systems contributes to climate change adaptation and mitigation by enhancing biodiversity, improving soil health, and sequestering carbon. This study evaluates the distribution, characteristics, socioeconomic benefits, and potential for climate resilience and mitigation through *R. prinoides* agroforestry, highlighting its role in advancing climate-smart agricultural practices in dryland ecosystems.

1.2 Problem Statement

Alternative production systems that enhance natural resources conservation, increase productivity, reduce emissions, sequester CO_2 and are resilient to the adverse impacts of climate change has been the objective of global society (IPCC 2014). Many efforts are underway mainly based on introduced (adopted) technologies to build a Resilient Green Economy (CRGE) (FDRE 2011) in Ethiopia. While locally practiced farming systems that integrate trees/shrubs on crop lands (agroforestry) can be alternative production systems towards climate-smart agriculture. Agroforestry could play a significant role in improving productivity and climate change adaptation and mitigation. The extent, attributes, and role and potential of agroforestry systems practiced in different parts of the world could vary due to biophysical and anthropogenic reasons (Mutuo et al. 2005). However, the characteristics and distribution potential of local or indigenous agroforestry practices, and context-specific evaluation of their role and potential in improving production, and adaptation to and mitigation of climate variability and change has been lacking and becoming a major focus in research and development (Sinclair and Coe 2019). Many ecosystem services and products provided by agroforestry practices are often not compensated financially (Graves et al. 2017; García de Jalón et al. 2017) and have not yet been well explored and appreciated. The lack of appreciation for local or indigenous agroforestry practices can be attributed to an incomplete understanding of the role these practices currently and potentially play in food production, local economies, and ecological balance, and sustainable agricultural development (Paul et al. 2017). Thus, study on locally practiced *R. prinoides*-based agroforestry can improve the understanding on the role and potential of the practice and similar local or indigenous best farming practices towards climate-smart agriculture.

Integrating trees into arable or livestock systems requires new skills, techniques and knowledge (Calfapietra et al. 2010). Lack of appropriate management practices and support can be barriers to the uptake (Martineau et al. 2016) and bring low productivity. The nature and extent of agroforestry practices are highly context-specific and dependent on many socioeconomic and biophysical factors, including education level, gender, age, landholding size, wealth status, soil fertility, and agro-climate (Adger et al. 2009; Bryan et al. 2009; Beyene et al. 2019). Profitability, household benefits, equity, sustainability, environmental services, markets for inputs and outputs, and institutions (property rights) influence the socio-ecological benefits of agroforestry (Alavalapati et al. 2001). Trees/shrubs cultivated in a mixture with annual crops and/or range/animal on the farm can have positive and negative effects on system components and users. Thus, research and development are required to overcome negative effects (trade-offs) and to foster positive outcomes by matching best-suited species or agroforestry practices to particular system niches and the interests of the landowners (Harja et al. 2006; Bukomeko et al. 2019). Narrow definition and lack of data on the extent of agroforestry have led to the misconception on the importance of agroforestry and exclusion in policy decisions concerning land use and environmental challenges (Rigueiro-Rodríguez et al. 2009) and there is a need to find reliable data on the extent of agroforestry at different scales (Zomer et al. 2009). Thus, characterizing and mapping distribution potentials of *R. prinoides*-based agroforestry are crucial to demonstrate its significance and identify potential agroecological niches in developing expansion and management plans, and implementation policies.

The low profitability of agroforestry systems is one of the most important implementation challenges (García de Jalón et al. 2017). Nowadays, the financial contributions of the outputs of the land uses are attracting good attention from the farmers. This is because of the increasing market demand for the output of the land uses and the capital by the households to contribute and maintain the households' basic provisions. The feasibility and benefits of agroforestry to smallholder farmers are currently under debate. Common ground can be found when evidence emerges that high production levels and economic values of agroforestry products may generate financial capital beyond subsistence levels aiding capital accumulation and reinvestment at the farm level (van Noordwijk et al. 2011; Thorlakson and Neufeldt 2012). Moreover, financial return is one of many other socioeconomic and biophysical factors that determine an agroforestry practice's feasibility, acceptability, performance, and continuity (Franzel 2004; van Noordwijk et al. 2011). Agroforestry adoption is based on sociocultural and socio-ecological considerations, including land tenure, and ecological services (McGinty et al.2008; Sood & Mitchell 2009). Thus, a study on the socioeconomic benefits, profitability, gender sensitivity and determinant factors of

R. prinoides-based agroforestry could demonstrate the socioeconomic feasibility of the practice and similar local or indigenous farming practices.

Despite its high potential, agroforestry has not yet been appreciated as a mitigation and adaptation mechanism and its uptake is slow due to several socioeconomic and technical challenges (Martineau et al. 2016; García de Jalón et al. 2017). The adaptation and mitigation potential of agroforestry systems is poorly studied (Verchot et al. 2007), particularly in drylands. Context-specific evaluation of agroforestry practices performance in the adaptation and mitigation of climate variability and change impacts has been lacking and become a major focus in research and development (Sinclair and Coe 2019). Agroforestry research can contribute to climate-proofed policy options that promote short-term and medium-term socioeconomic benefits which maintain flexibility while reducing vulnerability. To increase the extent of trees/shrubs on smallholder farms, new approaches to address adoption barriers such as secure land tenure and information gaps, and link agroforestry to climate, food security and development policies, are needed. Thus, a study on the role of locally practiced *R. prinoides*-based agroforestry in the adaptation to and mitigation of climate change in the drylands could reveal the potential of agriculture in the adaptation and mitigation of climate change through scaling up of similar local or indigenous tree-based farming practices.

1.3 Conceptual Framework: Climate-Smart Agriculture with *R. prinoides*-based Agroforestry

Agricultural practices relying on specialized systems such as annual crop mono-cropping and high-input farming have been driven by the pursuit of economic efficiency and reduced production costs. However, these systems often lead to unstable returns and are highly sensitive to external drivers of change, including climate variability (Keating et al., 2010; Falco and Chavas, 2008; Kim et al., 2012). In contrast, diversified production systems that incorporate trees and shrubs, such as agroforestry, are emerging as viable alternatives to stabilize agricultural returns, enhance resilience to climate extremes, and improve socioeconomic benefits (Gockowski and Asten, 2012; Kim et al., 2012; Abson et al., 2013; Garnett et al., 2013). The integration of trees and shrubs into farming systems has been highlighted in discussions on sustainable intensification as a key strategy to enhance both crop productivity and land management practices (Mueller et al., 2012; Gockowski and Asten, 2012; Garnett et al., 2013). In this context, tree-based farming systems, particularly those incorporating species like *Rhamnus prinoides*, are increasingly recognized for their potential to adapt to and mitigate the impacts of climate change (Hernández-Morcillo et al., 2018). This study focuses on the role of *R. prinoides*-based agroforestry in smallholder farming systems in the drylands of northern Ethiopia, comparing its performance with conventional mono-cropping systems. The study explores the potential benefits of incorporating *R. prinoides* into production systems for climate-smart agriculture, including increased productivity and carbon sequestration, as well as improved resilience to climate-induced risks.

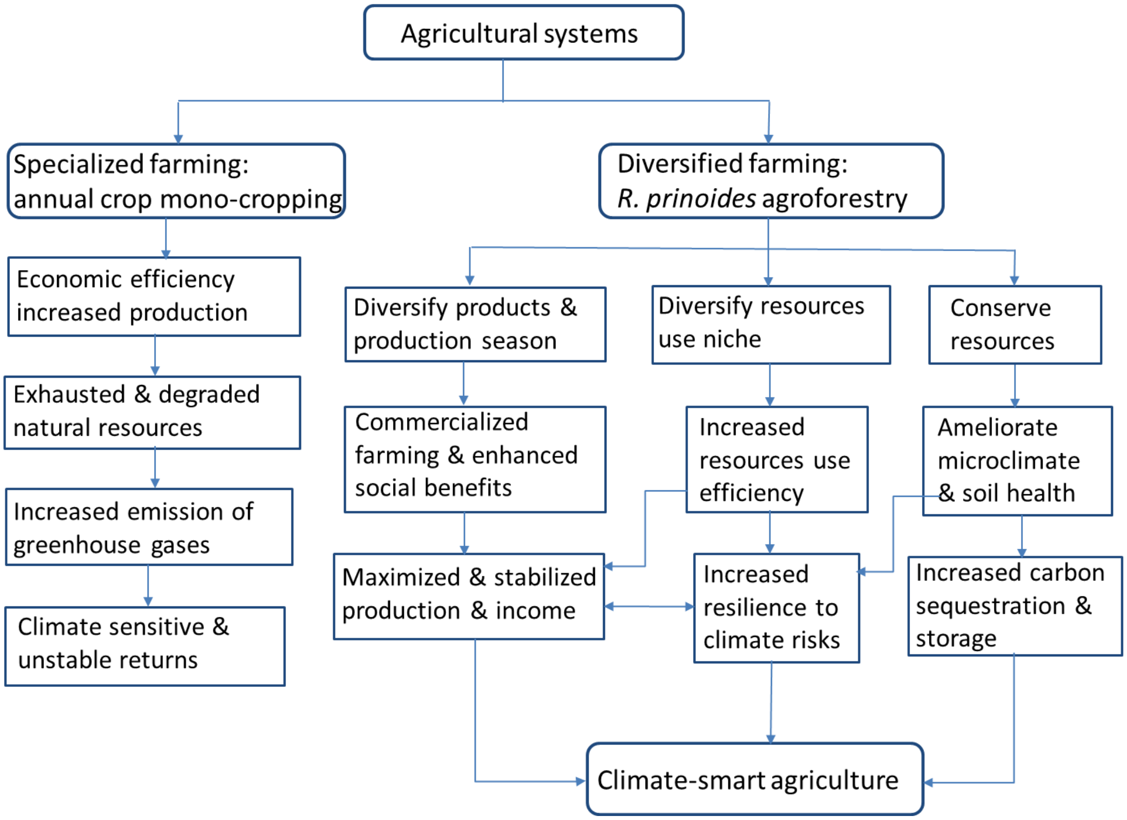

Figure 1. 1 Conceptual framework

1.4 Objectives

1.4.1 General objective

This dissertation investigates the role and potential of *Rhamnus prinoides*-based agroforestry practices among smallholder farmers for climate-smart agriculture in the drylands of northern Ethiopia.

1.4.2 Specific objectives

1. Assess the spatial distribution and characteristics of *R. prinoides*-integrated farming systems,
2. Evaluate the social and economic benefits derived from these systems,
3. Examine their role in adapting to climate variability, and
4. Explore their potential for mitigating climate change impacts

1.5 Research Questions

The study addressed the following research questions:

- How does the distribution of *Rhamnus prinoides* agroforestry vary across different agroecological zones over time in Tigray?
- How do the adoption and practice of *R. prinoides* agroforestry differ among households?
- What are the socioeconomic benefits derived from *R. prinoides* agroforestry for smallholder farmers?
- How does the profitability of *R. prinoides* agroforestry compare to that of annual crop mono-cropping systems?
- What role does *R. prinoides* agroforestry play in adapting to the impacts of climate variability?
- What are the biomass and soil carbon stocks associated with *R. prinoides* agroforestry practices?

1.6 Organization of the Dissertation

The dissertation is structured into chapters and sections. Chapter 1 is an introduction that states the background and justification, problem statement and objectives of the study. Chapter 2 is a literature review of existing theoretical and empirical knowledge on farming systems, climate change causes and impacts, climate resilient agricultural practices, agroforestry potential in adaptation and mitigation of climate change, and determinant factors. Chapter 3 deals with the methods and approaches of the study. Some of the methods are stated in general while indicated that details are presented in their respective chapters. Chapters 4 to 7 deal with the discussion of study findings by objectives. Chapter 4 discusses the distribution and characteristics of *R. prinoides-based* agroforestry while chapters 5 to 7 address its role in enhancing socioeconomic benefits, adaptation to climate variability impacts, and mitigation of climate change, respectively. Finally, Chapter 8 synthesizes the findings and concludes with lessons learned and recommendations.

Chapter 2 **Literature Review**

2.1 Farming Systems: Specialized (Annual Crop Mono-cropping) versus Diversified (Tree-based) Production Systems

A farming system in an area is influenced by various socioeconomic and environmental aspects. Biophysical and human factors that include agroecological suitability of agroforestry tree species and farmers' production objectives and decisions on species selection could determine the distribution and design of agroforestry systems. These factors include climate (Krebs 1994), soil moisture and nutrient content (Veenendaal and Swaine 1996), historical events, disturbances, interaction with local fauna, competition with other plant species for space and human influence (Bongers et al. 1999). For agroforestry species distribution, human influence may be a significant factor in comparison to natural vegetation. While the design and distribution of agroforestry system is the result of the environmental and anthropogenic factors combined effects, it is important to identify the major factors for planning and management. Assessment of plant distribution and abundance can serve to identify potential ecological niches for expansion and management (Dalle et al. 2002).

Agricultural practices based on highly specialized farms (annual crop mono-cropping and high inputs) have been driven by the search for increased economic efficiency, economies of scale, and reduced marginal costs of production (Abson et al. 2013). However, agricultural returns from specialized farming systems are unstable, and sensitive to different exogenous drivers of change (Keating et al. 2010; Falco and Chavas 2008; Kim et al. 2012; Abson et al. 2013). The uncertain weather conditions, the commodity markets (O'Brien and Leichenko 2000), and land degradation are causing farm returns to be less stable (FAO 2009). Diversified production systems (mixture of tree, crop, and animal) are hypothesized to maximize and stabilize agricultural returns and reduce production and income risk of extreme events (Gockowski and Asten 2012; Kim et al. 2012; Abson et al. 2013; Garnett et al. 2013). There are arguments that a diversified approach reduces volatility at the cost of reduced expected mean returns (Abson et al. 2013). However, diversified strategies that trade off the variance against mean returns can often be superior to highly variable systems (Philippi and Seger 1989; Abson et al. 2013). Lasco et al. (2014) stated that well-designed and properly managed diversified production systems have a positive impact on yield and income and the potential for sustained production.

A diversified farming system that harbors agro-biodiversity and integrates trees/shrubs in land use systems is important for sustainable intensification of agricultural production through improved crop and land management (Mueller et al. 2012; Gockowski and Asten 2012; Garnett et al. 2013). Diversified production systems like agroforestry systems could provide greater stability and buffer against production and income variability caused by unstable or extreme events through diversified enterprises with different sources of income and products (Hernández-Morcillo et al. 2018). Diversified farming systems that include trees on farms can provide an easily accessible, safe, and stable source of income, particularly for women (Thorlakson and Neufeldt 2012). Hence, this study intended to evaluate the socioeconomic significance of a diversified production system that includes significant tree components with higher value and the stability and sensitivity of its profits to drivers of change compared to annual crop mono-cropping in a smallholder farming system.

Modern farming systems based on highly specialized farms that rely on annual mono-cropping with high inputs are less resilient to climate variability impacts (Keating et al., 2010; Falco and Chavas 2008; Kim et al. 2012; Abson et al. 2013). Weather conditions and commodity markets have become increasingly erratic (O'Brien and Leichenko 2000), causing concerns that farm returns have become less resilient (FAO 2009). Diversifying production system is hypothesized to be a local strategy resilient to climate variability impacts (Elmqvist et al. 2003; Falco and Perrings 2005; Baumgärtner 2007; Verchot et al. 2007; Abson et al. 2013). Diversified production systems that include significant trees/shrubs can be resilient to climate variability impacts because of trees/shrubs' ability to maintain or modify their environment (van Noordwijk et al. 2021). Trees/shrubs can buffer climate extremes by reducing incident solar radiation and reducing air and soil temperature while improving water status, gas exchange and water use efficiency because of permanent tree cover, varied ecological niches and diverse functions (Bayala et al. 2008; Lott et al. 2009; Sida et al. 2018). Trees on farmland can increase water infiltration in the soil profile and reduce moisture stress during low rainfall years (Jose et al. 2009).

Trees-based systems can utilize off-season rainfall and residual soil water after the cropping period, which can increase water utilization efficiency (Lott et al. 2009). The perennially or woodiness of trees allows for the accumulation of growth resources and gains made in exploring belowground and aboveground resources through their root and canopy architectures can maintain production during wetter and drier years and reduce the risk of extreme events (Jose et al. 2009; van Noordwijk et al. 2021). A difference in leaf phenology can improve water utilization efficiency, gaseous exchange, tree growth and productivity of accompanying crops (Muthuri et al. 2009, Sida et al. 2018). Different species could support productivity at different times and ways and spread income and labor requirements (Isbell et al. 2011). Integrating trees into land use systems to improve crops and land management can be important for the sustainable intensification of agricultural production (Garnett et al. 2013; Sileshi et al. 2020). Context-specific evaluation of agroforestry practices performance in the adaptation of climate variability impacts has been lacking and become a major focus in research and development (Sinclair and Coe 2019).

2.2 Climate Change: Causes and Impacts

Climate change refers to a change in the state of the climate that can be identified by changes in the mean and the variability of its properties, which persists for an extended period, typically decades or longer (IPCC 2014). The increase in atmospheric carbon dioxide (CO_2) concentration is considered the predominant cause of global climatic change (Barrden and Jose 2012). Conventional agricultural practices in developing countries have played a major role in increasing the total global area of marginal land that is now substandard for the long-term production of food and livestock (FAO 1990) and has contributed significantly to the accumulation of greenhouse gases in the atmosphere (IPCC 2007). As a result, agriculture is considered a major contributor to GHG global emissions (Schaffnit-Chatterjee 2011). Annual GHG emissions from the agricultural sector in Ethiopia during 2001−2006 were estimated to be 50.9 million Mg CO_2e year^{-1} due to the conversion of native land to cropland, livestock production, use of nitrogen fertilizers and grazing area burned (Brown et al. 2012). If the current rate of land use conversion continues, GHG emissions from Ethiopia will increase from 150 million Mg CO_2e year^{-1} in 2010 to 400 million Mg CO_2e year^{-1} in 2030 (Bishaw et al. 2013). Hence the conversion of land from a forest ecosystem to an agricultural ecosystem has resulted in a change in the ecosystem services and functions the ecosystem can provide (Mikkelsen 2005).

Climate variability and extreme events are observed and expected to increase (Dazé 2014). Agriculture is generally one of the most affected sectors by climate change and variability (IPCC 2014). Ethiopia is highly exposed to climate change impacts (Conway and Schipper 2011) and placed at the top of most vulnerable countries (Krishnamurthy et al. 2014). The vulnerability of Ethiopian agriculture to climate change and variability is attributed to environmental, socio-demographic, and economic factors (Dercon 2004; Deressa 2010). Future climate change and variability are likely to slow down agricultural growth and thereby reduce opportunities for economic development and eradication of poverty (Wagesho et al. 2013; Dazé 2014). High levels of poverty and extreme dependence on natural resources have exposed smallholder farmers of Ethiopia to the adverse impacts of climate change. Thus, a proper adaptation strategy to climate change is urgent in different parts of Ethiopia.

Alternative production systems that reduce emissions, sequester CO_2 and are resilient to the adverse impacts of climate change have been the objective of global society (IPCC 2014). Cultivated lands have the potential to contribute significantly to climate change mitigation by improved cropping practices and greater numbers of trees on farms. The global estimated potential of all greenhouse gas (GHG) sequestration in agriculture ranges from 1500 to 4300 Mt CO_2e year $^{-1}$, with about 90% of this potential lying in soil carbon restoration and avoided net soil carbon emission (Smith and Wollenberg 2012). The priority of smallholder farmers is strongly on food security; climate mitigation measures will need to demonstrate support for improved food production and climate adaptation benefits. Agroforestry could be a win-win solution to the seemingly difficult choice between environmental and agricultural land use because it increases carbon storage and may also enhance agricultural productivity in a changing climate (Kumar and Nair 2012).

2.3 Agroforestry Systems and Practices

Agroforestry is defined as the deliberate integration of woody species with crops and/or pastures on the same land-unit resulting in the integration of Economic and ecological interactions between components (Young 2002). Growing of trees in combination with crops was a common practice dating back to the beginning of plant and animal domestication. Since then, several models of various agroforestry practices, from Asia, Africa and Europe to North and South America, have been developed (King 1987). Agroforestry practices were promoted as a sustainable land-use management system. For example, agroforestry practices range from low-input systems such as alley cropping and short-term improved fallow with leguminous shrubs to shade-grown coffee (Coffee Arabica) in tropical regions and high-input cereal-legume systems and riparian plantings in temperate biomes (Nair 1993; Gordon & Newman 1997).

Agroforestry systems are unique because they are a land management practice that simultaneously addresses biophysical, economic, and socio-ecological components. Such diversity and interactions lead to a greater functional and structural complexity than conventional agroecosystems (Nair 1993). However, agroforestry adoption is based on socio-cultural and socio-ecological considerations including land tenure and land rights, as well as providing enhanced biodiversity and ecological services (McGinty et al. 2008; Sood & Mitchell 2009). Currently, agroforestry practices are increasingly embraced due to their potential to provide ecosystem services. Ecosystem services provide an economic incentive value to society by maintaining environmental sustainability (FAO 2007).

Agroforestry practices that provide ecosystem services, are a means of diversifying agricultural production and increasing food security for smallholder producers, especially under current climate change scenarios (Verchot et al. 2007). Although maintaining agricultural productivity under changing climatic conditions will be challenging (Watson et al. 2000), Sanchez (2000) suggested that structurally and functionally complex agroecosystem management systems, including agro forestry practices, may show greater resilience to changing environmental conditions.

2.4 Role of Agroforestry in Climate Change Adaptation

Adaptive capacity can be defined as the potential or capability of a system to adjust to climate change, including climate variability and extremes, to moderate potential damages, to take advantage of opportunities, or to cope with the existing environmental conditions (Mortimore and Manvell 2011). Current climate change and variability contribute to reduced agricultural production and productivity, and the future sustainability of the sector in the area depends on the types of coping and adaptation strategies employed (Alemayehu and Bewket 2016). Reduced vulnerability thereby sustainable development is gained by improving the adaptive capacity (Smit 2006).

Watson et al. (2000) and Sanchez (2000) suggested that structurally and functionally complex agro-ecosystem management systems, including agroforestry practices, may show a greater resilience to changing environmental conditions. If well managed, agroforestry can play a crucial role in improving resilience to uncertain climates through microclimate buffering and regulation of water flow (Nguyen et al. 2013). Smit (2006) reported that climate change and variability impacts are well buffered by agroforestry practices because of permanent tree cover and varied ecological niches. The potential for building resilience and adapting to climate change through agroforestry practices is particularly promising for smallholder farmers in the developing world who are most vulnerable to its effects (Verchot et al. 2007). Agroforestry can provide resilience to smallholder farmers for the most component of climate change i.e. increased inter-annual variability in rainfall and temperature. Moreover, tree-based production systems often produce crops of higher value than raw. Hence, trees in the agroecosystem may help buffer against production and income risks.

Trees on farms enhance the smallholder farmers coping with and adapting capacity to climate risks through crop and income diversification, soil and water conservation, and efficient nutrient cycling and conservation (Action Aid 2008). Tree-based systems have some advantages of maintaining production during wetter and drier years through their deep root system that can explore a larger soil volume for water and nutrients. This can help during droughts, increase soil porosity, reduce runoff, and increase soil cover leading to increased water infiltration, and can reduce moisture stress in the soil profile during low rainfall years (Jose et al. 2009). Agroforestry contributes to ecosystem functions in water recycling by increasing rainfall utilization compared to annual cropping systems. Lott et al. (2009) reported that about 25% of the water transpired by trees is used during the dry season, that they can utilize off-season rainfall (comprising 15–20% of the total annual rainfall) and residual soil water after the cropping period. This complementarity between trees and crops extend soil moisture uptake, making soil resource utilization more efficient than in pure monoculture (Lehmann et al. 1998).

Microclimatic improvement through agroforestry has a major impact on crop performance as trees can buffer climatic extremes that affect crop growth. Trees are valuable during droughts and floods. Many trees together will lower temperatures in the nearby area and maintain aerated soil conditions by pumping excess water out of the soil profile more rapidly than other production systems (Temesgen 2009). In particular, the shading effects of agroforestry trees can buffer temperature and atmospheric saturation deficit reducing exposure to supra-optimal temperatures, under which physiological and developmental processes and yield become increasingly vulnerable (Lott et al. 2009). Scattered trees in agroforestry farms can enhance understory growth by reducing incident solar radiation, and air and soil temperature, while improving water status, gas exchange and water use efficiency (Bayala et al. 2008).

Agroforestry practices can diversify and enhance agricultural production and increase food security of producers, particularly under climate change scenarios (Verchot et al. 2007). Besides, Olson et al. (2000) reported that incorporating woody plants into crop, forage, and livestock operations provides greater resiliency to this inter-annual variability through crop diversification produced seasonally and increased resource-use efficiency. Moreover, diversifying the production system to include a significant tree component with higher values may buffer against income risks associated with climatic variability (Verchot et al. 2007). Thus, agroforestry systems can provide greater economic stability and reduce risk under climate change by creating more diversified enterprises with greater income distribution over time (Cubbage et al. 2012).

2.5 Role of Agroforestry in Climate Change Mitigation

Mitigation of adverse climate change lies in the potential for carbon sequestration, soil carbon restoration, and avoidance of net soil carbon emission (Seneviratne et al. 2015). The Intergovernmental Panel for Climate Change has recognized the high potential of agroforestry in carbon sequestration can be increased up to 90-150 tones C ha^{-1} year^{-1} over a potential area of 900 million ha (Garrity 2004; Leakey 2010). Agroforestry systems have 3 to 4 times more biomass than traditional treeless agricultural systems with carbon stocks ranging from 29-228 Mg C ha^{-1}year^{-1} (Matocha et al. 2012; Mbow et al. 2014). Global estimates for the C sequestration potential of agroforestry systems over 50 years period range between 1.1 and 2.2 Pg C ha^{-1} year^{-1} (Dixon, 1995) with larger suitable areas for agroforestry worldwide that substantially greater potential than existing systems (Zomer et al. 2009). Compared to mono-cropping, agroforestry systems are more efficient in capturing the resources available at the site for biomass growth and may result in higher C inputs to the soil (Nair et al. 2010). Higher soil organic carbon (SOC) pools in agroforestry systems can be particularly achieved by increasing the amount of biomass C returned to the soil and by strengthening soil organic matter (SOM) stabilization or by decreasing the rate of biomass decomposition (Lal 2005; Sollins et al. 2007; Rasse et al. 2005). Agroforestry systems store more C in deeper soil layers near trees than away from trees (Nair et al. 2010; Kell 2012). The effectiveness of agroforestry practices in storing carbon depends on environmental and socioeconomic factors (Mutuo et al. 2005).

From an agroforestry point of view, C sequestration involves primarily the uptake of atmospheric CO_2 during photosynthesis and the transfer of fixed C into vegetation, detritus, and soil pools for ‘‘safe’’ storage. In agroforestry systems, CO_2 occurs in two major segments: above and below ground. In turn, the above ground can be partitioned into specific plant parts (stem, leaves, etc. of trees and herbaceous components), and the below ground into living biomass such as roots and other belowground plant parts, soil organisms, and C stored in various soil horizons (Nair 2011). The total amount sequestered in each part differs greatly depending on several factors including the region, the type of system (nature of components and age of perennials such as trees), site quality, and previous land use (Nair 2011).

Table 2. 1 Potential C stock and C sequestration of some agroforestry systems (AFS) in Africa

Description of AFS	C sequestration (Mg C $ha^{-1}yr^{-1}$) [range]	C stock (Mg C ha^{-1}) [range]	Max rotation period (yr)
Parklands dominate AFS (*Faidherbia albida*)	0.5 [0.2–0.8]	33.4 [5.7–70.8]	50
Rotational woodlots	3.9 [2.2–5.8]	18.5 [11.6–25.5]	5
Tree planting-windrows-home gardens	0.6 [0.4–0.8]	19.0 [ns]	25
Long-term fallows, regrowth of woodlands in abandoned farms	2.24 [0.22–5.8]	15.7 [ns]	25
AFS and integrated land use	3.12 [1.0–6.7]	77.9 [12–228]	50
Soil C in AFS	0.9 [0.25–1.6]	90.7 [13–300]	Ns

Source: Mbow et al. (2014), ns: not specified

2.5.1 Aboveground Agroforestry Trees/Shrubs Carbon Pools

This component represents the most easily and reliable carbon pool in agroforestry and captures the carbon sequestration in aboveground biomass. The aboveground carbon sequestration rates in some major agroforestry systems around the world are highly variable, ranging from 0.29 - 15.21 Mg $ha^{-1}yr^{-1}$ (Nair et al. 2010) and differ greatly depending of several factors, like the agro-climatic region, the type of system, site quality, previous land use, management practices adopted. In general agroforestry systems on arid, semi-arid, and degraded sites have a lower carbon sequestration potential than those on fertile humid sites; and the temperate agroforestry systems have relatively lower sequestration potential compared with the tropical systems (Srinivasarao et al. 2013). Estimates of aboveground C-sequestration potential (CSP) assume that 45% to 50% of branch and 30% of foliage dry weight constitute C (Shepherd and Montagnini 2001; Schroth et al. 2002).

Carbon (C) in living tree biomass is accumulated through photosynthesis, where the trees assimilate atmospheric CO_2 and transform it into carbohydrates. When the tree is decomposed or burned, the absorbed C is released into the atmosphere as CO_2 (Palm 2009). In the terrestrial system, the amount of C stored in soils is almost three times larger than in aboveground biomass, and roughly twice the size of the C in the atmosphere (Eswaran et al. 1993). The rise of CO_2 in the atmosphere and the possible warming of the climate are mainly caused by anthropogenic activities and disturbance of soils which have led to changes in the fluctuations of CO_2 (Schlesinger 2000). Forests play an important part in the C cycle of the earth, and the terrestrial biosphere has the potential to store carbon and mitigate CO_2 emissions at an extent comparable with 11-15 % of the emissions released from fossil fuels (Singh and Lal 2000).

2.5.2 Belowground Agroforestry Trees/Shrubs Carbon Pools

Trees add organic matter to the soil system in various manners, whether in the form of roots, or litter-fall, or root exudates in the rhizosphere (Nair et al. 2009). These additions are the chief substrate for organisms involved in soil biological activity and interactions, with important effects on soil nutrients and fertility. In participating in these complex processes, trees contribute to carbon accumulation in soils and are increasingly present in discussions on mitigating greenhouse gases associated with global warming and climate change. Although carbon (C) constitutes almost 50% of the dry weight of branches and 30% of foliage, the greater part of C sequestration (around 2/3) occurs belowground, involving living biomass such as roots and other belowground plant parts, soil organisms, and C stored in various soil horizons (Takimoto et al. 2008).

Trees have extensive root systems which can grow deep into the mineral soil. The root-derived C inputs are critical for the SOC pool in deeper soil horizons (Kell 2012). Specifically, root-derived C is more likely to be stabilized in the soil by physicochemical interactions with soil particles than shoot-derived C (Rasse et al. 2005). In addition to deep soil C inputs, another reason for the promotion of SOC sequestration in agroforestry systems is that tree roots have the potential to recover nutrients from below the crop rooting area. The resulting enhanced tree and crop plant growth by a subsequent increase in nitrogen (N) nutrition may result from an increase in SOC sequestration (van Noordwijk et al. 2015). The changes in microbial decomposer community composition under N-fixing trees may result in greater retention of relatively stable SOC (Resh et al. 2002). N-fixing trees in mixtures with non-N-fixing trees may develop deeper root profiles due to niche partitioning (da Silva et al. 2009). Mixed tree plantings in agroforestry systems may enhance SOC sequestration as increases in tree species diversity may potentially increases fine root productivity (Meinen et al. 2009; Schroth 1999). Further, higher species richness and tree density can increase SOC contents in agroforestry systems (Saha et al. 2009).

2.5.3 Role of Agroforestry in Reduction of Non-Carbon GHG Emission

Incorporating leguminous tree species on farmland could improve soil fertility, and reduce the use of chemical fertilizers, and reduce GHG emissions. Allen et al. (2009) reported that silvopasture increased nutrient efficiency and reduced N fertilizer inputs that resulting in a reduction of CH_4 and N_2O emissions. Similarly, Thevasthasan et al. (2004) reported that a fast-growing poplar-based intercropping system improved the N cycle and reduced N fertilizer input that resulting in N_2O emission reduction.

Table 2. 2 The potential for annual N_2O reduction eight years after the establishment of trees, based on the N cycling budget developed for growing poplar-based intercropping system

Causes of N_2O reduction	N fertilizer saved (Kg ha^{-1})	N_2O emission reduction (Kg ha^{-1})
10% less land area	8	0.1
N cycling in tree-based intercropping	7	0.09
Reduction N leaching	20	0.5
Total N_2O reduction potential		0.69

Source: Thevasthasan et al. (2004)

2.6 Synergy of Mitigation and Adaptation to Climate Change through Agroforestry

Agroforestry practices were promoted as a sustainable land-use management system in developed and developing countries (Nair 1993; Gordon and Newman 1997). Agroforestry systems are unique because they are a land management practice that simultaneously addresses biophysical, economic, and socio-ecological components. Such diversity and interactions lead to a greater functional and structural complexity than conventional agroecosystems (Nair 1993; McGinty et al. 2008; Sood and Mitchell 2009). Agroforestry practices are increasingly adopted due to their potential to provide ecosystem services. Ecosystem services provide an economic incentive to society by maintaining environmental sustainability (FAO 2007). Agroforestry in general may increase farm profitability through improvement and diversification of output per unit area of tree/crop/livestock, through resilience against damaging effects of climate change and variability, products added to the financial diversity and flexibility of the farming enterprise (Molua, 2005) can also substantially contribute to climate change mitigation (Smith and Wollenberg 2012).

Table 2. 3 Implications of some agroforestry practices on mitigation and adaptation of climate change

		Mitigation	
		Positive	Negative
Adaptation	Positive	○ Component diversification for ecological or sustainable intensification of production, ○ Component diversification to bridge seasonal gaps ○ Component diversification to buffer production and income risks ○ Component diversification for commercial products, ○ Component diversification for income diversification, ○ Soil carbon sequestration and storage, ○ Improved water use and holding capacities, ○ Use of manure and N-fixing trees instead, ○ Reduced inputs (nitrogen fertilizer) ○ Labor intensive: labor division and distribution, ○ Value adding and market networking (premium price)	○ Dependence on biomass energy, ○ Overuse of ecosystem services, ○ Increased use of mineral fertilizers, ○ Poor management of nitrogen and manure, ○ Over extraction of non-timber products, ○ Timber extraction, ○ Fuelwood harvesting and charcoal production for sale (income source)
	Negative	○ Integral protection of forest reserves, ○ Limited rights to agroforestry trees, ○ Forest plantation excluding harvest	○ Use of forest fires for pastoral and land management, ○ Tree exclusion in farming lands, ○ Market failure, ○ Insecure tree tenure

Adapted from Mbow et al. (2014)

Generally, recent literature has taken the view that agroforestry can serve a role in mitigating climate change and helping farmers adapt to the effects of climate change. Agroforestry practices produce assets for farmers, combined with opportunities for climate change mitigation and the potential to promote sustainable production that enhances agroecosystem diversity and resilience under changing climate (Table 2.4). Agroforestry plays a significant role in two key dimensions of climate change; mitigation of greenhouse gas emissions and adaptation to changing environmental conditions (Garrity 2004; Morgan et al. 2010; Schoeneberger 2005). Besides, FAO (2006) further emphasized that agroforestry presents an opportunity to counter the adverse impacts of climate change through the joint action of adaptation and mitigation. The use of multipurpose trees and integrated approaches can enhance the profitability of agroforestry (Nguyen et al. 2013), for example, trees can be sources of fodder, which in turn is converted into valuable plant nutrients (Neupane and Thapa, 2001) and reduce the use of chemical fertilizer that resulting reduction of GHG emission. Trees on farms can provide wild edible fruits (Assogbadjo et al. 2012) and non-timber products that serve as alternative food during periods of deficit and primary sources of income for many rural communities (Neufeldt et al. 2012), while sequestering and storing carbon and reducing emissions.

Table 2. 4 Synergy of climate change mitigation and adaptation through agroforestry

Agroforestry benefits	Livelihood	Mitigation	Adaptation
Carbon benefit	[Income]	+++	+
Wood energy	[Asset]	+++	++
Buffer climate risks/water recycling	[Asset]	++	+++
Improve ecosystem resilience/microclimate/soil fertility	[Asset-Income]	+	+++
Ecosystem services: food/fruit/medicine	[Asset-Income]	*	+++
Reduce pressure on natural forest	[Asset-Income]	+++	+

+++ high positive impact, ++ positive impact, + limited positive impact, * zero positive or potential negative impact (source: Mbow et al., 2014)

2.7 Biophysical and Socioeconomic Determinants of Agroforestry

The nature and magnitude of agroforestry system practices are highly context-specific and dependent on many socioeconomic and biophysical factors including level of education, gender, age, soil fertility, landholding and wealth status (Adger et al. 2009; Bryan et al. 2009), profitability, household benefits, equity, sustainability, environmental services, markets for inputs and outputs, and institutions (property rights) influence (Alavalapati et al. 2001). Agricultural production is highly influenced by the peak season (of cultivating and harvesting), climate variability, pests and diseases, and varied production factors (varied soil conditions) (Soren 2007). These require intensive labor, adjusting farming activities (the right time for plowing, sowing, and harvesting) based on weather forecasts, monitoring and timely treatment, and crops and input suitability, respectively. The farmer is an entrepreneur to allocates resources between different crops and different animal production, combine the different inputs profitability, and choose between different production methods which involve different levels of investments (Soren 2007). Agricultural performance depends on the willingness and ability of the farmers to make the right decision at the right time. Benefit, enabling biophysical and socioeconomic environment and knowledge could play a great role in determining the practice of certain farming systems than others.

The propensity to adapt and the choice of adaptation strategies are highly context-specific and dependent on many factors including level of education, gender, age, soil fertility, landholding and wealth status (Adger et al. 2009; Bryan et al. 2009). Therefore, understanding the perceptions of local communities regarding climate variability (Maddison 2006; Bryan et al. 2009), the determinants of farmers' choices of adaptation strategy (Lambrou and Nelson 2013; Ashraf et al. 2014), and evaluating local adaptation mechanisms and integrating them with scientific and technological advancement (Nyong et al. 2007; Kasali 2011) is required to design and promote socially acceptable and locally effective coping and adaptation strategies (Denton 2002; Lambrou and Nelson 2013).

2.8 Theoretical Framework

This study adopts the social–ecological systems framework to analyse the distribution and cahractersitics of agroforestry practice, and its socioeconomic benifts, adaptation and mitigation potentials. Inherent to the theory of social–ecological systems, the human sphere and the environment are interconnected and can be conceptualized as a social–ecological system (McGinnis and Ostrom 2014; Partelow 2018). At landscape level, agroforestry is an example of a social–ecological system (SES) that has evolved over centuries and created co-benefits for people and nature (Torralba et al. 2018; Elbakidze et al. 2021). In application of this conceptualization, agroforestry landscapes may be understood as a social–ecological system, where farmers adopt the practice of agroforestry to benefit from the resulting interaction between the woody vegetation and the agricultural crops and/or livestock (Torralba et al. 2018; Klimke et al. 2024). A social-ecological systems framework views agroforestry systems as a complex interplay between human societies and the environment, recognizing that both factors are interconnected and influence each other. This framework emphasizes the importance of understanding the social dimensions, such as farmers' decisions, cultural practices, and institutional arrangements, alongside the ecological dimensions, including biodiversity, soil health, and climate change. By using a social-ecological systems framework, agroforestry can be more effectively designed and implemented to address the complex challenges of food security, environmental sustainability, and social equity. By considering both social and ecological factors, this framework helps to develop more sustainable and effective agroforestry practices that benefit both people and the environment.

Chapter 3 Methodology

3.1 Study Site Description

The study was conducted in the Ahferom and Ganta-afeshum districts in the Central and Eastern zones of the Tigray region, northern Ethiopia. Ahferom and Ganta-Afeshum districts are located 14^0 08' 43" to 14^0 11' 47" N and 38^0 53'55" to 38^0 57' 30’’ E and 13° 41'50" to $13^0$15’20″ N and 39° 42'08" to $39^0$49′ 09″ E, respectively (Figure 3.1).

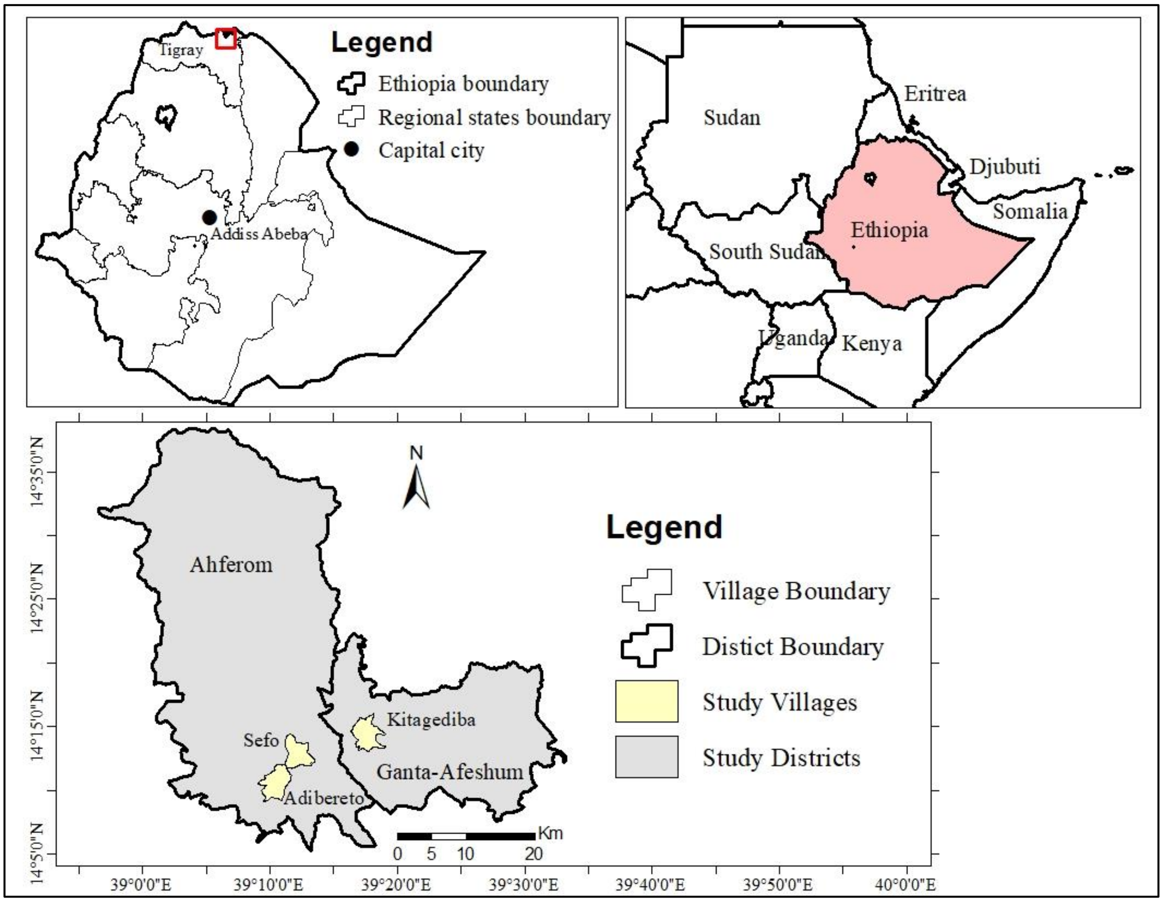

Figure 3. 1 Map of the study site, showing the location of study villages and districts in the regional state of Tigray, Ethiopia (Developed using ArcMap10.81).

Ahferom and Ganta-Afeshum are neighboring districts with similar topographic settings, edaphic, and agro-climatic conditions. The districts are characterized by rugged topography with wide altitudes ranging from 1400 to 3200 m and wide agro-climatic zones: lowlands (1400 - 1700 m), midlands (1700 – 2200 m) and highlands (2200 – 3200 m) (BoARD 2010). The midlands and highlands of the districts are suitable for *R. prinoide* production in rain-fed and irrigation systems.

The rainfall distribution of the study areas is mostly unimodal. The study area corresponds to the tropical drylands with annual rainfall ranging from 450 to 850 mm, with a mean rainfall of 650 mm and monthly average minimum and maximum temperature ranges from 8 to 14°C and 24 to 28°C, respectively (Figure 3.2).

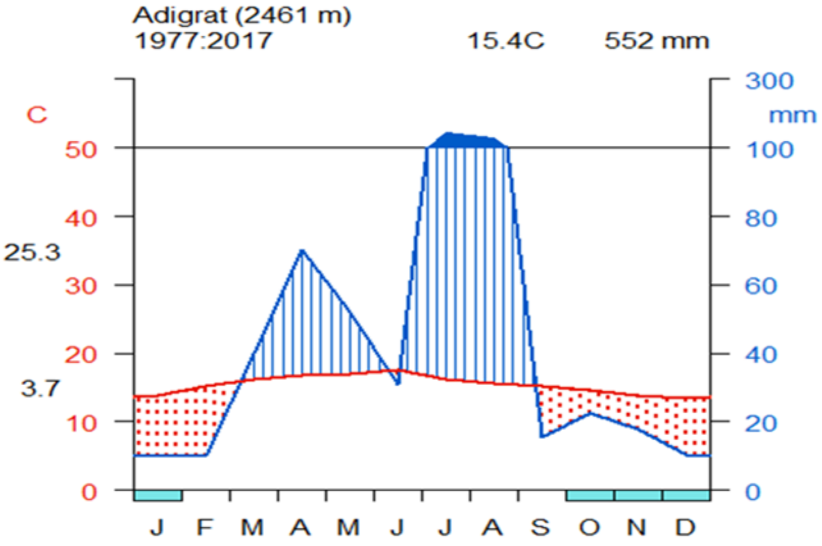

Figure 3. 2 Monthly rainfall and temperature of the study area (source: National Metrological Agency, Mekelle Branch, 2018). Adigrat metrological station was used as a reference for analyses because it was the nearest possible to the study areas with similar topographic and climatic conditions and better data for a prolonged time.

The dominant soil types in the Ahferom and Ganta-Afeshum districts are regosol and cambisol and by texture vary in ranges of clay, clay loam, sandy loam, and silty loam (BoARD 2010). The major land cover and land use types are woodland, evergreen scrub, open woodland, bushland, grassland, cropland, bare soil, and rock outcrop (BoARD 2010). Sedentary mixed farming is the main livelihood system of the rural society. The districts are widely practicing *R. prinodes* intercropping in the midlands and highlands and are characterized as *R. prinoides* (Gesho) belt by the Bureau of Agriculture and Rural Development (BoARD). The number of *R. prinoides* trees that farmers own used to determine their wealth status in the community. It is the main source of cash income for the community members. The two districts are the most densely populated (340 people/km^2) with the smallest landholding (≤ 0.5 ha) per household (BoARD 2010) in the Tigray region and highly exploited because of age-old agricultural practice.

3.2 Sampling Strategy

A reconnaissance survey was conducted in the Tigray region districts across agroecology based on key informants and unpublished reports to record *R. prinoides* occurrence points and select study sites with wider *R. prinoides* agroforestry practice (Figure 3.3). Three sites found in the highlands of Ahferom and Ganta-Afeshum districts that have a similar topographic setting, edaphic and climatic conditions, and farming system with wider *R. prinoides* agroforestry practice in the rain-fed farming system were selected as replicates to conduct socioeconomic surveys, inventory and soil sampling. The sites are Sefo, Adibereto, Kitagedeba (Figure 3.1) in the highlands (with altitudes of 2563, 2558, and 2559 m above sea level, respectively) and with plateau-type topographic setting suitable for farming practices. The soil type in the sites is regosols and silt loam by texture (BoARD 2010). The sites have similar average annual rainfall (650 mm) and average temperature (18°C). Rain-fed *R. prinoides* intercropping primarily with Wheat is the common farming practice. Sample size was estimated based on Yamane (1967) formula;

$$n = \frac{N}{1+N(e)^2} \qquad (3.1)$$

where n = sample size, N = total households, and e = level of precision.

Proportional numbers of households were randomly selected for the survey from each site because baseline data on practicing and non practicing farmers were not available. Accordingly, 75 from 747, 66 from 656 and 50 from 505 households were randomly sampled from Sefo, Adibereto and Kitagedeba villages, respectively. Thus, 191 respondents were selected out of a total of 1908 households in the targeted villages. The list of respondents included 134 *R. prinoides* agroforestry practicing while 57 non-practicing.

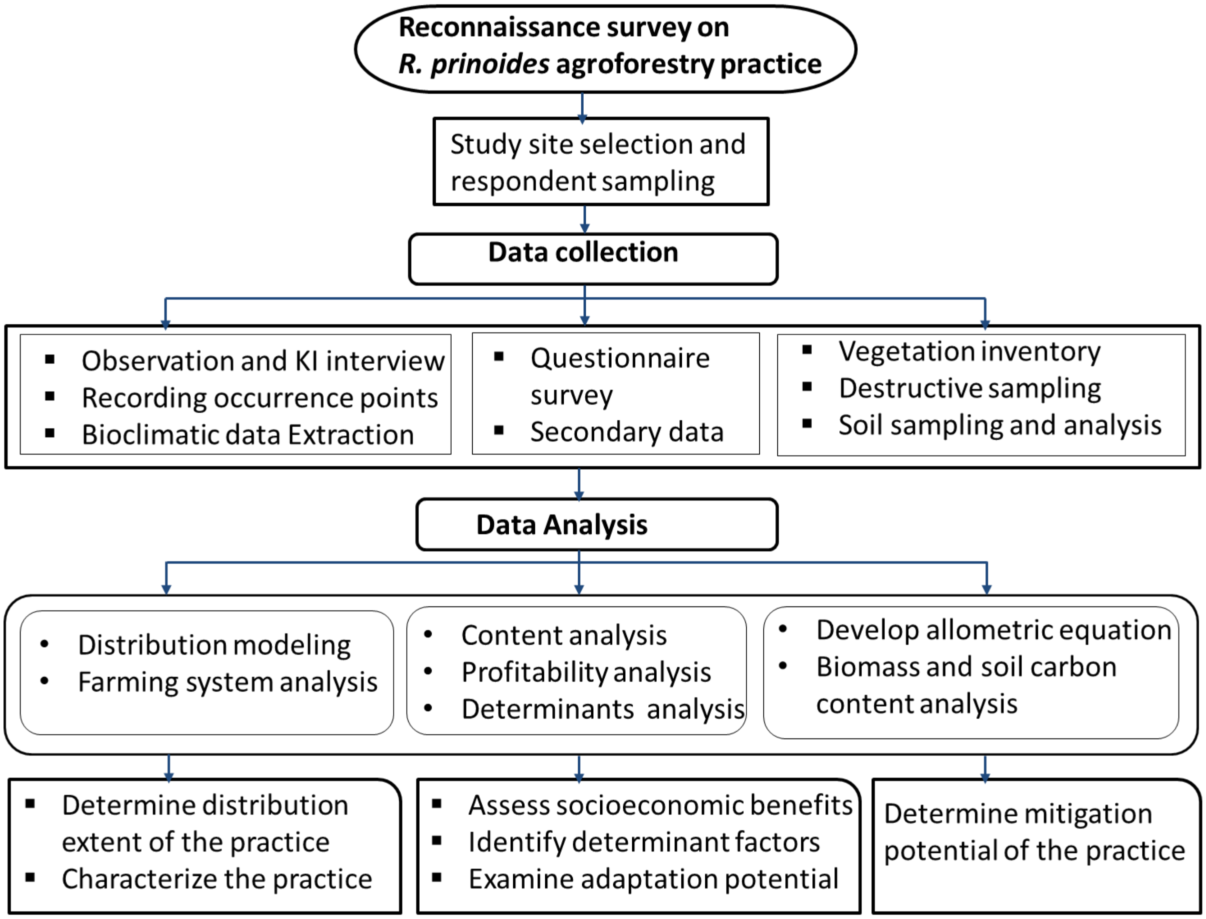

Figure 3. 3 Methodological framework showing methods of data collection, the type of data collected, data analysis and chapters produced based on the collected data and analysis

3.3 Data Collection

The primary data was collected using a socioeconomic survey, field observation, and measurement, vegetation inventory, and laboratory analysis. The literature review was made to collect available secondary information and regional and global experiences. A semi-structured questionnaire was developed and improved after the pilot survey. A household survey was conducted to collect information that includes the purpose of *R. prinoides* planting and its management system, socioeconomic contribution, adaptation potential, and determinants (Sections 4.2.2, 5.2.1, and 6.2.1, respectively). Field observation and measurement accompanied by key informant interviews were conducted to collect information on the spatial arrangement of components, extent, distribution, and performance of *R. prinoides*-based agroforestry (Sections 4.2.2 and 5.2.1, respectively). Laboratory analysis was conducted to collect information on soil status as a distribution factor and soil carbon content (Sections 4.2.2 and 7.2.4, respectively). Regional weather data was collected from national and global sources (Sections 4.2.2).

3.4 Data Analysis

Qualitative and quantitative analysis was used for data collected through inventory, interviews and observations. Enterprise-specific budget (cost and benefit analysis) was done to assess the profitability of *R. prinoides* agroforestry (Section 5.2.2). Allometric models were developed for *R. prinoides* to estimate the biomass stock of *R. prinoides* agroforestry (Section 7.2.3).

The determinants of practicing *R. prinoides* agroforestry, its extent in area, and the number of trees per household were analyzed using binomial (glm), linear (lm), and Poisson (glm) regression models, respectively. Factors influencing the number and choices of farmers' coping and adaptation measures were examined using Poisson and binomial regression models, respectively. The factors hypothesized affecting *R. prinoides* agroforestry practice and adaptation strategy choices were related to socioeconomic and biophysical characteristics of households and their locality (Table 3.1) motivated based on a review of literature on agricultural practices and available data at hand. Studies in different parts of Africa showed that age, education, family size, gender, wealth status, landholding, soil fertility, labor, credit access, extension service, and distance to markets are important determinants of practicing agricultural technologies (Bryan et al. 2013; Berman et al., 2015; Opiyo et al. 2016).

A binary logistic regression model through maximum likelihood estimates of parameters was applied to identify determinant factors to practicing *R. prioniodes*-based agroforestry and different coping and adaptation strategies by smallholder farmers. The backward regression method was employed to select factors with statistical significance ($P < 0.1$) for the binomial regression modeling. The model is given as;

$$\ln\left[\frac{P}{1-P}\right] = \alpha + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n \tag{3.2}$$

Where $\ln\left[\frac{P}{1-P}\right]$ is the odds (likelihoods) ratio, α is the intercept, $\beta_1, \beta_2 \ldots \beta_n$ are the coefficients to be estimated, and $X_1, X_2 \ldots X_n$ denotes the set of explanatory variables related to socioeconomic and biophysical factors hypothesized to influence the practice of *R. prinoides-based* agroforestry and choices of coping and adaptation strategies.

Besides, factors influencing the number of *R. prinoides* trees planted, planting density and the number of coping and adaptation strategies practiced by households were examined. The Poisson regression model was employed to account for the count-dependent variable. This can be specified as:

$$AN_i = \beta X_i + \varepsilon_i \tag{3.3}$$

where AN_i is the number of *R. prinoides* trees planted and the number of coping and adaptation strategies practiced by household i. X_i is denoted as a vector of socioeconomic and biophysical variables that are hypothesized to affect the number of *R. prinoides* trees, planting density, and the number of coping and adaptation strategies.

Table 3. 1 Description of the socio-economic and biophysical factors hypothesized to influence the extent of *R. prinoides* agroforestry practice by smallholder farmers

Factors	Description	Mean (SD)	Expected Impact	Literature
Gender	Gender of the household head (0 = female, 1= male)	0.75 ± 0.44	+ve	Asfaw et al. (2004)
Age	Age of household head (years)	50.37 ± 9.12	+ve	Maddison (2006); Deressa et al. (2009)
Education	Years of education of household head	3.61 ± 2.85	++ve	Asfaw et al. (2004)
Family size	Number of household members	4.32 ± 1.79	+ve	Croppenstedt et al. (2003); Deressa et al. (2009)
Land ownership	0 = own land, 1= parent land	0.15 ± 0.33	-ve	Gbetibouo et al. (2010); Fosu-Mensah et al. (2012)
Farm size	Size of farm holding (ha)	0.61 ± 0.16	+ve	Deressa et al. (2009)
Farm fertility	Soil depth (0 = deep, 1= medium, 2 = shallow)	0.78 ± 0.62	--ve	Fosu-Mensah et al. (2012)
Farm parcels	Number of farm plots (fragments)	1.97 ± 0.82	-ve	
Wealth status	0= higher income, 1= middle income, 2= low income	1.32 ± 0.57	--ve	Knowler and Bradshaw (2007); Deressa et al.(2009)
Climate awareness	Familiar to climate change (0= no 1= yes)	0.90 ± 0.30	++ve	Maddison (2006)

SD is standard deviation, +ve, ++ve, –ve and --ve represent possible positive and negative impacts at varied level, respectively

Chapter 4 Distribution and Characteristics of *R. prinoides*-based Agroforestry Practice in Tigray, Ethiopia

4.1 Introduction

Integrating trees with crops and livestock on the farmlands and rangelands in agroforestry is an age-old practice. An appropriate spatial and temporal arrangement of trees/shrubs is important in agroforestry. The tree and crop species and management methods chosen influence decisions on agroforestry design (Madalcho and Tefera 2016; Lelamo 2021; Tadesse et al. 2021). This integration practice allows the landowners to develop an investment for spreading production and income risks through diversification (Paul et al. 2017; Hernández-Morcillo et al. 2018*)*. The basic tenets of a sustainable agroecosystem are the conservation of renewable resources, adaptation of the crop to its environment, and maintenance of a high and sustainable level of productivity (Koohafkan et al. 2012; Plieninger et al. 2020). Designing such agroecosystems means ensuring fundamental ecosystem functions in agricultural fields. Agroforestry systems have been shown to enhance these functions (Plieninger et al. 2020; Reith et al. 2020).

An accurate and objective estimate of the extent and geographical distribution of different agroforestry types is crucial to demonstrate their significance in developing management plans and implementing policies. Assessment of plant distribution and abundance can help to identify potential ecological niches for expansion and management (Dalle et al. 2002). Agroforestry is widely distributed and there is a need to find reliable data on the extent of agroforestry at different scales (Zomer et al. 2009). The lack of data and narrow definition of agroforestry have led in the past to the misconception on the importance of agroforestry and this in turn has led to agroforestry not being included in policy decisions concerning land use and environmental challenges (Rigueiro-Rodríguez et al. 2009). This problem can best be tackled by providing an objective estimate of the distribution of agroforestry. This is especially important since agroforestry has recently gained recognition in research and policy circles. The revived interest in agroforestry originates from an increasing amount of evidence of environmental (Palma et al. 2007a, b; Rigueiro-Rodríguezet al. 2009; Cardinael et al. 2015), social and economic (Mercer et al. 2014; Ranca et al. 2014) benefits of this land use system.

Agroforestry can be classified based on components, spatiotemporal arrangements, products, agroecological zones, and socioeconomic groupings (McAdam et al. 2009; Mosquera-Losada et al. 2009). Agroforestry systems have some degree of beneficial effect on yield and income and potential for sustained production when well designed and properly managed (Lasco et al. 2014). Some well-designed agroforestry system attributes include a compatible combination of components, appropriate spatiotemporal arrangement, and suitable management techniques. Thus, the tools that are available to a farmer for optimizing water balance, nutrient cycles, and positive interaction are the selection of plant (and animal) species, their spatial and temporal arrangement (system design), and their management (Schroth et al. 2003; Teixeira et al. 2003). Farmers have substantial and invaluable experiential knowledge about their farming systems (Madalcho and Tefera 2016; Hamore and Lemage 2019).

In an area, various environmental and socioeconomic factors influence the distribution and design of agroforestry systems. The distribution of agroforestry systems is affected by biophysical and human factors including the agroecological suitability of agroforestry tree species and farmers' production objectives and decisions on species selection. These factors include climate (Ranjitkar et al. 2016; Odeny et al. 2019), altitude, topographic setting (Dalle et al. 2002; Odeny et al. 2019), soil moisture and nutrient content (Russo et al. 2007; Gue`ze et al. 2013), historical events, disturbances, interaction with local fauna, competition with other plant species for space and human influence (Bongers et al. 1999; Dalle et al. 2002). Human influence may be a significant factor for the distribution of agroforestry species compared to the natural vegetation. Although the combined effects of environmental and anthropogenic factors determine agroforestry system design and distribution, it is important to analyze the major determinants, to understand the potential areas for planning and management.

Agroforestry has an important role to play in integrating livelihood and conservation objectives (Leakey 2012). However, trees/shrubs cultivated in a mixture with annual crops and/or range/animal on the farm can have positive and negative effects on system components and users. Thus, research and development are required to overcome negative effects (trade-offs) and to foster positive (socioeconomically and environmentally optimal) outcomes. This can be done mainly by matching best-suited species to niches and the interests of the landowners (Harja et al. 2006; Bukomeko et al. 2019). This coincides with 'the right tree in the right place for a clear function' slogan (Harja et al. 2006). This requires understanding the characteristics that make specific trees/shrubs compatible with different farming landscape niches and identifying or devising management techniques that enhance the compatibility of the species to niches under changing climates. *Rhamnus prinoides*-based agroforestry system is an indigenous farming practice by smallholder farmers in the drylands of northern Ethiopia. However, little is known about the practice's current and future potential distribution, its design and management systems, and the determinant factors while it has been providing different products and services to the community. Thus, assessment of *R. prinoides* agroforestry practices distributions, and exploring its attributes are important to identify potential agroecological niches for expansion, best practices to be scaled-up and limitations to be improved.

Therefore, this study aimed at examining the distribution and characteristics of *R. prinoides-based* agroforestry practice by smallholders in the drylands of northern Ethiopia to facilitate expansion and management planning, and scaling-up of best practices. Specifically, this study aimed to (1) assess current and predict future macro-distribution of *R. prinoides* agroforestry under climate change scenarios; (2) analyze the micro-distribution of *R. prinoides* agroforestry across altitudinal gradient; (3) identify the nature and arrangement of components, and the local management techniques of *R. prinoides-based* agroforestry among practicing farmers and (4) examine biophysical and socioeconomic factors that determine the distribution and characteristics of *R. prinoides* agroforestry in the study area.

4.2 Methodology

4.2.1 Sampling Strategy

A reconnaissance survey was conducted in Tigray region districts based on secondary reports and key informant discussion on the presence of *R. prinoides* to record occurrence points for macro-distribution mapping (the species distribution at Tigray level) and to identify sites with wider *R. prinoides* agroforestry practice. Then, three sites found in Ahferom and Ganta-Afeshum districts with wider altitudinal ranges (1700 m to 2800m asl) and better *R. prinoides* abundance were purposively selected to study the micro-distribution (the species distribution at site level) and characteristics of *R. prinoides*-based agroforestry practices. For critical field observation and measurements, three transect walks were laid out two km apart in each study site across an altitudinal gradient (Figure 4.1). In each transect, three sample plots (20×20 m) were placed in each of the upper (>2200m), middle (1900-2200m), and lower (1700-1900m) strata of transects with 50m spacing along the counter for inventory and soil samplings. The length and stratum position of transects are different within and among the sites because of the varied topographic setting that resulted in different upper and lower ends.

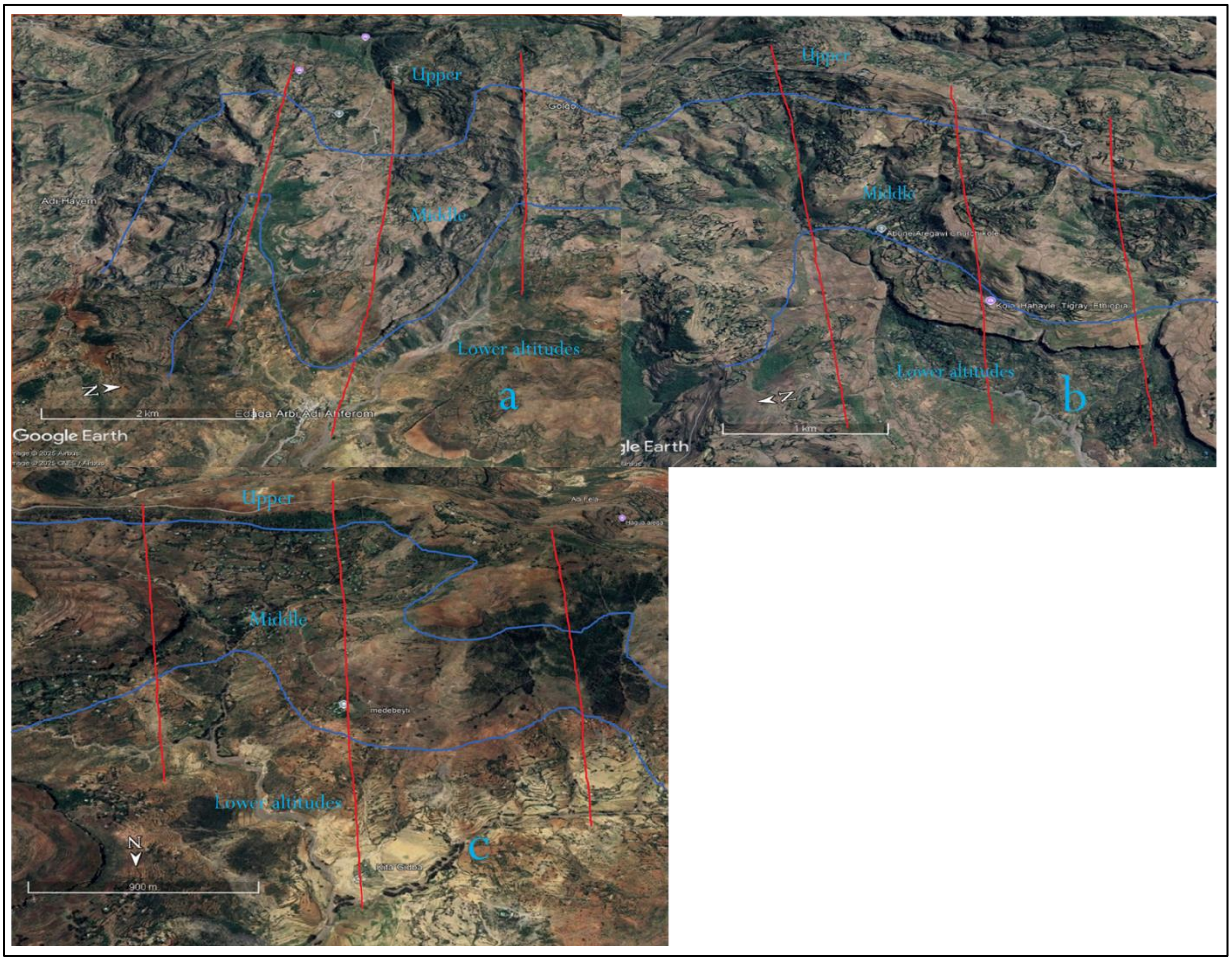

Figure 4. 1 Illustration of the topographic settings (upper, middle and lower altitudes) and observation transects across altitudinal gradients of the study sites: Sefo (a), Adibereto (b) and Kitagedba (c) with their downstream (Images taken from Google Earth Pro).

4.2.2 Data collection

Distribution Model and Environmental Factors

The maximum entropy algorithm (MaxEnt ver. 3.4.4) was employed to predict the distribution of *R. prinoides*-based agroforestry in Tigray. This is because it is among the best-performing models that require relatively small input data (Elith et al. 2011), is less susceptible to multi-collinearity problems (Phillips et al. 2006), precise, and showed the best predictive capacity (Leal-Nares et al. 2012). The model requires species occurrence points and environmental factors as input. Field visits to all districts that reported practicing *R. prinoides* planting were carried out across agroecologies to collect presence data. Accordingly, a total of 102 *R. prinoides* occurrence points with a minimum distance of one km from each other as recommended by Veloz (2009) were recorded using a portable global positioning system (GPS-Garmin 72 H). The occurrence points were saved in comma-separated value (.CSV) format of Microsoft Excel for MaxEnt input.

A total of 20 environmental (altitude and 19 bioclimatic) variables obtained from the WorldClim database (http:// www.worldclim.org/version2.14) at 30 arc seconds (1 km^2) resolution for current (1970-2000), 2050 (2041-2060) and 2070 (2061-2080) (Table 1) were considered for the analysis of midterm and future distribution of *R. prinoides-based* agroforestry in Tigray. For the future projection, the Global Climate Model of BCC-CSM2-MR and Model for Interdisciplinary Research on Climate (MIROC6) of two shared socio-economic pathways (SSP245 and SSP585) were chosen because of their lower and higher greenhouse gas emission scenarios, respectively (Riahi et al. 2017). The extracted environmental variables were transformed from raster to ASCII format using ArcGIS10.8.1 for MaxEnt input. To reduce multi-collinearity problems, one of the pairs of environmental variables with Pearson correlation $|R| > 0.8$ and with a lower contribution in the model was omitted. Accordingly, 10 of 20 environmental variables were retained to predict the suitable agro-ecologies for *R. prinoides-based* agroforestry in Tigray (Table 4.1 and 4.2).

Table 4. 1 The environmental variables employed in MaxEnt to predict the distribution of *R. prinoides-based* agroforestry in Tigray

Variables	Code	Data sources	Resolution	Unit
Altitude/Elevation	DEM	SRTM DEM Global	30 arc s	Meter
Annual mean temperature	Bio_1	WorldClim	30 arc s	°C
Mean diurnal range	Bio_2	WorldClim	30 arc s	°C
Isothermally (Bio2/Bio7*100)	Bio_3	WorldClim	30 arc s	Percent
Temperature seasonality (SD*100)	Bio_4	WorldClim	30 arc s	°C
Max temperature of the warmest month	Bio_5	WorldClim	30 arc s	°C
Min temperature of the coldest month	Bio_6	WorldClim	30 arc s	°C
Temperature annual range (Bio5-Bio6)	Bio_7	WorldClim	30 arc s	°C
Mean temperature of the wettest quarter	Bio_8	WorldClim	30 arc s	°C
Mean temperature of the driest quarter	Bio_9	WorldClim	30 arc s	°C
Mean temperature of the warmest quarter	Bio_10	WorldClim	30 arc s	°C
Mean temperature of the coldest quarter	Bio_11	WorldClim	30 arc s	°C
Annual precipitation	Bio_12	WorldClim	30 arc s	Mm
Precipitation of the wettest month	Bio_13	WorldClim	30 arc s	Mm
Precipitation of the driest month	Bio_14	WorldClim	30 arc s	Mm
Precipitation seasonality (CV)	Bio_15	WorldClim	30 arc s	Percent
Precipitation of the wettest quarter	Bio_16	WorldClim	30 arc s	Mm
Precipitation of the driest quarter	Bi0_17	WorldClim	30 arc s	Mm
Precipitation of the warmest quarter	Bio_18	WorldClim	30 arc s	Mm
Precipitation of the coldest quarter	Bio_19	WorldClim	30 arc s	Mm

Field Observation and Measurements

The existing presence data of *R. prinoides*-based agroforestry practices was collected from primary and secondary sources to determine its potential distribution. The field visit was conducted to most areas reported practicing *R. prinoides* agroforestry to collect data that include GPS points, altitudinal gradient (agroecological setting), growing season, and cultivation culture of the specific localities. In addition, topographic setting (upper, middle, and lower altitude), soil depth (shallow, medium, and deep) and *R. prinoides* abundance (count), farmland position (homestead or field), farming system (rain-fed or irrigation) and aspect (south, north, west, and east) were collected from the plots placed in the transects laid out across altitudinal gradient through observation and measurement. GPS-Garmin 72 H was used to collect geographical coordinates, altitude, and aspects while meter tape was used to estimate soil depth.

Soil Sampling and Analysis

A composite soil sample (from four corners and center) was taken from the 20 cm of soil surface of each plot placed in the upper, middle, and lower parts. The samples were stored in polythene bags. An undisturbed soil sample was taken using a core sampler with 100 cc from all plots at one randomly selected sampling point from the upper soil depth (20 cm) to analyze soil moisture and bulk density. A total number of 54 soil samples (27 disturbed and 27 undisturbed) from each site and 162 soil samples from three sites were taken. The soil samples were delivered to Mekelle University soil labs, for selected physical and chemical soil analyses.

Based on the procedures stated in Van Reeuwijk (2008), soil analyses for: Organic carbon content by the wet oxidation method of Walkley and Black; total nitrogen by the Kjeldahl method; Available P by Olsen method; Available K by neutral ammonium acetate extraction; Soil pH and EC in a 1:2.5 soil to water suspension; Texture by the Hydrometer method were done. Undisturbed soil samples were analyzed for: soil moisture content by oven drying at 105 °C for 24 hours and bulk density by weighing oven-dried (105 °C) soil samples with known volume (Brady and Weil 2002). The soil depth above the parent rock was estimated based on local farmers' experience, and local openings (such as gully or riverbanks).

Household Survey

Both closed and open-ended questionnaires were developed and improved after the pilot survey. Primary data was collected through household surveys. Respondents were asked questions on the *R. prinoides-based* agroforestry practices components, spatiotemporal arrangement, local or indigenous management techniques, ecological and economic interaction, and chronology and trends. Each respondent was asked for an opinion on why each component, arrangement, and management system was selected. Every response was recorded as an observation. For each of the respondents, there were 191 frequency observations, each having values ranging from 0 (when not mentioned), and 191 (when mentioned by all). Additional primary data was also collected from field observations with the interviewee accompanied by measurement of planting spacing and arrangement, sample tree dendrometer (canopy, stump diameter, height) and harvest estimate, and key informant interviews with at least three key informants that includes district experts, extension (development) agents (DA) and local administrators in each study sites.

4.2.3 Analysis Method

Macro-distribution Modeling

The CSV-formatted occurrence points and the selected ASCII-formatted environmental variables were introduced to the MaxEnt model and executed to predict the current and future potential distribution of *R. prinoides-based* agroforestry in Tigray (Steven et al. 2017). Model prediction was performed using the complementary clog-log output format, 15,000 background points, 10 replicate runs, and 500 iterations with randomly varying model training (80%) and testing points (20%). Response curves and Jackknife tests developed in the final optimal model were used to examine the relationship between the predictor variables and agro-ecological suitability, and the importance of the variables, respectively (Baldwin 2009). The area under the curve (AUC) of the receiver operating characteristic (ROC) which ranges from 0 to 1, is used to assess the predictive performance of the MaxEnt model (Hernandez et al. 2008; Gao et al. 2021). Accordingly, the predictive accuracy of the model can be categorized as failure (0.50 - 0.60), average accuracy (0.60 - 0.70), relatively accurate (0.70 - 0.80), very accurate (0.80 - 0.90), and extremely accurate (0.90 - 1.0) (Hernandez et al. 2008; Anderson et al. 2011).

The prediction maps of the MaxEnt model for five considered climate scenarios generated as raster files depict the presence probability of the species with continuous values ranging from 0 to 1, where 0 and 1 indicate unsuitable and suitable agroecologies, respectively (Young et al., 2011). This presence probability was classified into five equal-sized categorical classes with a 0.2 value threshold (Not suitable ≤ 0.2, Least suitable > 0.2, Moderate suitable > 0.4, High suitable > 0.6, and Very high suitable > 0.8) (Li et al., 2020) using ArcGIS 10.8.1. The area under each of the classified categories was calculated using ArcMap algebra, whereby the area of the pixels at the latitudes in the study area was equal to 0.84 km^2 resulting from the projected predictor variables pixel resolution of 0.916 × 0.916 km.

Micro-distribution Analysis

Regression methods are preferred as a practical method for summarizing species distribution along environmental gradients (Peeters and Gardeniers 1998). The relationship between the abundance of *R. prinoides* and the environmental variables was analyzed to identify factors affecting *R. prinoides* distribution. Analysis of variance was carried out to investigate for significant relationships between the abundance of the species and land condition and topographic features.

Pearson's correlation coefficients were used to analyze the relation between the abundance of *R. prinoides* and various environmental factors. To identify the most important factors that affect the distribution of *R. prinoides* a backward stepwise multiple linear regression analysis was performed.

$$Y = a + b1X1 + biXj + \varepsilon i \qquad (4.1)$$

where Y is the number of *R. prinoides*, X_j is altitude and soil variables, a is the intercept, b_i estimate of each variable

Farming Characteristics Analysis

Qualitative and descriptive statistics were used for the analyses of data collected through inventory, interviews and observations to characterize *R. prinoides-based* agroforestry. Wilcoxon rank-sum test and Kruskal-Wallis test were used to compare the mean score of *R. prinoides-based* farming attributes given by practicing farmers.

4.3 Results

4.3.1 Macro-distribution of *R. prinoides-based* Agroforestry Practice in Tigray

The AUC value of 0.952 for the current climate model indicated that the model performed with better accuracy and reliability than the random model which has an AUC value of 0.5 (Young et al. 2011). The AUC values for the future climate models were greater than 0.954 indicating better accuracy and reliability of the model prediction performances.

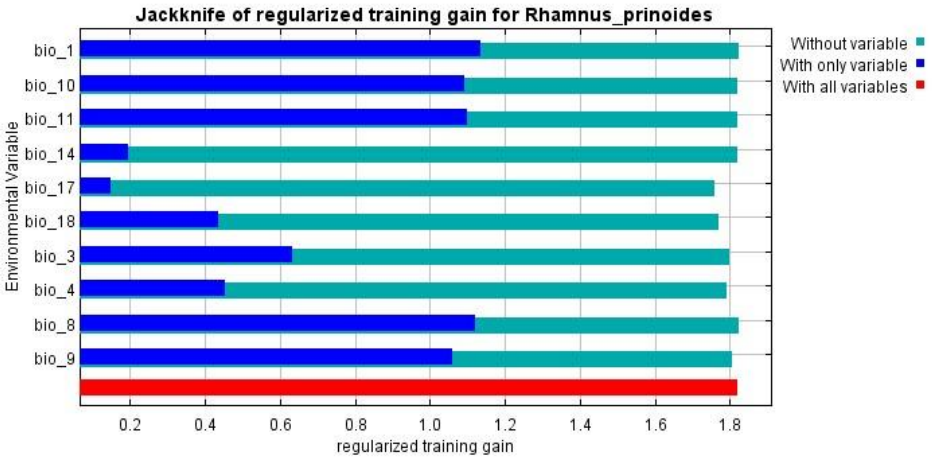

Figure 4. 2 Jackknife test of regularized training gains contribution of the considered environmental variables and their importance for agroecological suitability prediction of *R. prinoides*-based agroforestry

Temperature explained 76% of the variation in the distribution of *R. prinoides-based* agroforestry (Table 4. 2). The temperature variables surplus other variables with the highest gain when used in isolation and the precipitation variables outweighed other variables on the decreases of gain when omitted from the prediction models (Figure 4.2).

Table 4. 2 Variables with a higher contribution in modeling the current distribution of *R. prinoides-based* agroforestry

Variable	Code	Percent contribution	Permutation importance
The mean temperature of the warmest quarter	bio_10	35.2	8.2
The mean temperature of the wettest quarter	bio_8	16.1	0
Precipitation of the driest month	bio_14	15.1	2.5
Annual mean temperature	bio_1	7.5	1.2
The mean temperature of the coldest quarter	bio_11	6.8	51.1
The mean temperature of the driest quarter	bio_9	6.2	5
Precipitation of the driest quarter	bio_17	5	18.1
Precipitation of the warmest quarter	bio_18	3.9	5.5
Isothermally (Bio_2/Bio_7)	bio_3	2.4	3.2
Temperature seasonality	bio_4	1.9	5.3

The total potentially suitable agroecology with values > 0.2 for the *R. prinoides-based* agroforestry in Tigray under the current climate is estimated at 12,366.48 km^2 (Table 3), which accounts for 22.63% of the total area of the region. The practice mainly suits the highlands and midlands of Southern, Eastern, Central, Northwest, and Western Zones in Tigray (Figure 4.3).

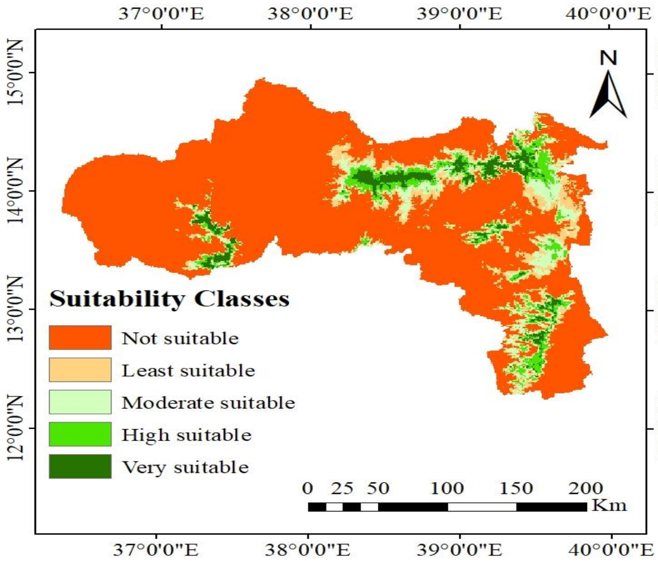

Figure 4. 3 Agroecological suitability of *R. prinoides*-based agroforestry in Tigray under the current climate (1970-2000)

Climate change is most likely to influence the future distribution of *R. prinoides*-based agroforestry in Tigray (Table 4.3 and Figure 4.4). The predicted suitable agroecologies under the current climate scenario (12,366.48 km^2) are expected to decrease by 1.43% and 2.24% under SSP245 and SSP585, respectively, by 2070.

Table 4. 3 Agroecological suitability classes (AESC) distribution area (Km^2) based on the predicted probability of occurrence values of *R. prinoides-based* agroforestry under current and future climate scenarios

Climate Scenarios	AESC-1	AESC-2	AESC-3	AESC-4	AESC-5	Total Suitable Area
Current climate	42276.40	4121.04	3613.68	2767.80	1863.96	12366.48
SSP 245 (2050)	43296.10	4156.32	3018.12	2399.04	1773.24	11346.72
Rate of change (%)	2.41	0.86	-16.48	-13.32	-4.87	-8.24
SSP 585 (2050)	42983.60	4043.76	3501.12	2573.76	1540.56	11659.20
Rate of change (%)	1.67	-1.88	-3.11	-7.01	-17.35	-5.72
SSP 245 (2070)	42452.8	4145.4	3351.6	3083.64	1609.44	12190.08
Rate of change (%)	0.42	0.59	-7.25	11.41	-13.65	-1.43
SSP 585 (2070)	42552.70	4158.84	3357.48	2844.24	1729.56	12090.12
Rate of change (%)	0.65	0.92	-7.09	2.76	-7.21	-2.24

AESC-1= Not suitable agro-ecology (≤0.2), AESC-2= Least suitable agro-ecology (0.2-0.4), AESC-3= Moderately suitable agro-ecology (0.4-0.6), AESC-4= High suitable agro-ecology (0.6-0.8), and AESC-5= Very high suitable agro-ecology (>0.8)

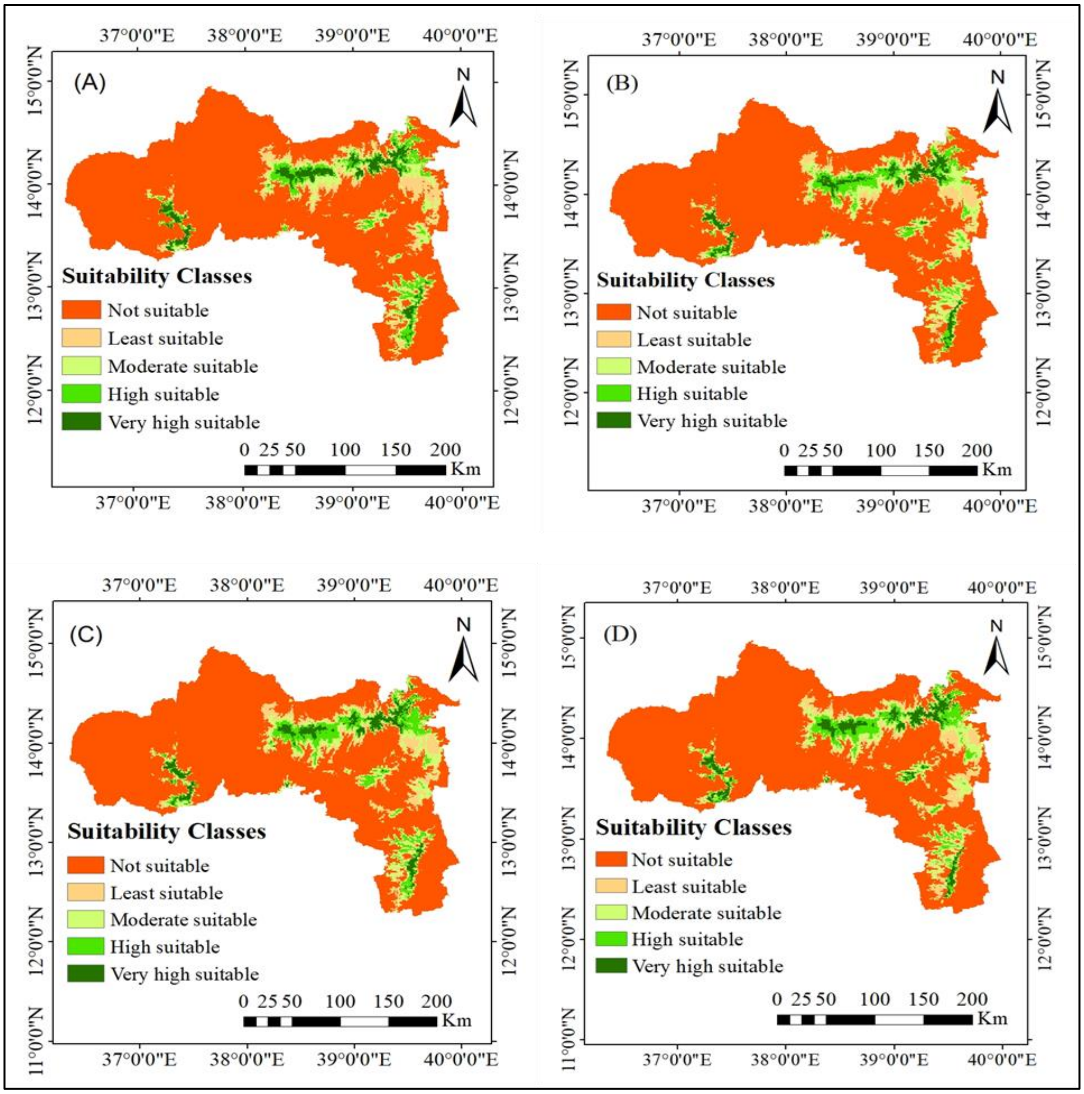

Figure 4. 4 Predicted agroecological suitability of *R. prinoides*-based agroforestry under future climate scenarios: (A) = SSP 245, (B) = SSP 585 of 2050 and (C) = SSP 245, (D) = SSP 585 of 2070.

The *R. prinoides-based* agroforestry in the highlands and midlands was observed at varied extents and management systems. The highlands and midlands of Ahferom, Ganta-Afeshum, and Medebay-Zana districts had higher abundance and distribution of *R. prinoides.*

4.3.2 Micro-distribution of *R. prinoides-based* Agroforestry Practice

The distribution of *R. prinoides* showed significant differences among topographic settings (Table 4.4). *R. prinoides* on farm plots in the upper altitude were significantly higher than the middle and lower altitudes ($P < 0.01$). The *R. prinoides* in the upper and middle altitudes were in a rain-fed farming system and the *R. prinoides* in the lower altitude were in an irrigation farming system limited to riverbanks or watersides. The number of *R. prinoides* plants per farm plot was similar between slope categories and farming systems. Farmlands with gentle slopes and rain-fed farming were dominant (Table 4.4).

R. prinoides agroforestry was similarly distributed in all aspects while it was not observed in areas with whole-day sunlight exposure. Besides, farmers reported that farmlands exposed to whole-day sunlight are not suitable for *R. prinoides* planting in rain-fed farming. The distribution of *R. prinoides* showed significant differences among farm plots with different soil depths ($P < 0.05$). *R. prinoides* abundance on farmlands with deeper soil was significantly higher than on farmlands with medium and shallow soil depth. Farmers indicated that farmlands with shallow soil depth are not good for planting *R. prinoides*. Moreover, the distribution of *R. prinoides* showed significant differences with farm plots' distance from residence ($P < 0.01$). The abundance of *R. prinoides* on farmlands near the homestead was significantly higher than on farmlands far from the residence.

Table 4. 4 The effect of topographic setting and farm condition on the abundance of *R. prinoides* measured on-farm plots of 400 m^2 (N = 81 plots).

Factors	Attributes	N	Mean	SD	F	Sig.
Topographic position	Upper (>2200 m)	27	20.704^a	13.764		
	Middle (1900–2200 m)	27	12.333^b	12.369	5.457	0.006
	Lower (1700-1900 m)	27	10.518^b	9.779		
Slope ranges (%)	Flat (0-3)	9	15.394^a	12.626		
	Gentle (4-12)	66	7.667^a	11.247	1.483	0.233
	Rolling (13-30)	6	15.167^a	15.065		
Aspect	North	21	12.857^a	11.477		
	South	18	18.167^a	12.585	0.649	0.586
	West	18	13.888^a	12.170		
	East	24	13.708^a	14.475		
Farm distance	Homestead (*Dihribet*)	60	17.017^a	13.171	9.887	0.002
	Field (*Wefri*)	21	7.381^b	8.078		
Soil depth	Deep soil (>1m)	33	19.182^a	12.269		
	Medium soil (0.5-1m)	33	12.091^{ab}	12.187	4.247	0.018
	Shallow soil (< 0.5m)	15	9.600^b	12.362		
Farming system	Rain-fed	60	15.083^a	13.665	0.452	0.503
	Irrigation	21	12.905^a	9.726		

One-way ANOVA analysis at 0.05 level and attributes of each factor with different superscripts along the columns are significantly different

The distribution of *R. prinoides* on farmland was significantly and positively correlated with altitude, soil moisture content (MC), electrical conductivity (EC), organic carbon content (OC), available potassium (K), available phosphorus (P), and available nitrogen (N). Sand content and bulk density (BD) were significantly and negatively correlated with the distribution of *R. prinoides* on farmland (Table 5). Soil bulk density (BD), organic carbon (OC), and potassium (K) contents had a significant effect on the distribution of *R. prinoides* on farmlands (Table 4.5).

Table 4. 5 Pearson correlation coefficient (r) between *R. prinoides* abundance and selected variables of farm plots (N=81) and backward linear regression (lm) analysis on their effects

Soil Variables	Ranges	Mean	SD	r	lm
Altitude (m)	1957.00 - 2693.00	2316.26	225.72	0.320**	
Sand (%)	19.00 - 55.00	37.37	7.55	-0.248*	
Silt (%)	19.00 - 45.00	32.48	6.21	0.207	
Clay (%)	20.00 - 44.00	30.15	4.90	0.119	
BD (g cm^{-3})	1.03 - 1.55	1.25	0.13	-0.342**	-25.4*
MC (%)	2.00 - 34.10	15.09	6.94	0.251*	
pH	5.91 - 7.73	6.70	0.51	-0.173	
EC (µs cm^{-1})	127.75 - 1215.00	400.93	207.73	0.592**	
OC (%)	0.57 - 5.67	2.34	1.144	0.592**	5.84*
Mg (mg kg^{-1})	250.00 - 2280.00	1338.15	509.13	0.079	
Ca (mg kg^{-1})	140.00 - 4480.00	2525.56	1251.90	0.011	
K (mg kg^{-1})	50.99 - 691.22	335.82	184.88	0.276*	0.015*
Na (mg kg^{-1})	30.38 - 334.18	113.83	56.78	-0.006	
N (mg kg^{-1})	172.24 - 1250.00	534.70	289.58	0.233*	
P (mg kg^{-1})	199.39 - 2987.76	746.61	622.29	0.348**	

Pearson correlation and backward linear regression analysis, **Significant at the 0.01 level, *significant at the 0.05 level

4.3.3 Nature and Arrangement of Components of *R. prinoides-based* Agroforestry

Intercropping *R. prinoides* as a perennial crop with annual crops in rain-fed farming systems was extensively practiced in the study area. Several farmers (70.2%) plant *R. prinoides* on crop fields. *R. prinoides* is a perennial plant with a lifespan of up to 50 years. *R. prinoides* is cultivated on farmlands while there is an attempt to plant on exclosure areas (communal lands) by youth user group associations. Farmers planted *R. prinoides* mainly for its leaves harvest. *R. prinoides* was observed to be a tree/shrub with dense leaves (green) in the dry season (Figure 4.5a) and terminates its lateral and apical shoots (dominances) and sheds its leaves (facilitated by harvesting) in the rainy season (Figure 4.5c) and begins to re-vegetate (budding) after the end of the rainy season. Practicing farmers cultivate annual crops that include wheat, beans, maize, and barley in association with *R. prinoides* (Table 4.6), and teff and sorghum were mentioned as less preferred for intercropping. Some of the criteria mentioned by most farmers for selecting the associated crops were resistance to shading effect and birds' damage, less competition for resources, and better productivity.

Figure 4. 5 *R. prinoides* agroforestry in scattered planting at the homestead in the dry season (a) and in row planting at the field in the early and late cropping season (c and d) in rain-fed and irrigation farming (b)

Most of the farmers (98.5%) planted *R. prinoides* on farmlands located at the homestead (Figure 4.5a) while some farmers (28.4%) cultivated on farmlands located in the field (Figure 4.5b & c). Besides, most farmers (84%) planted *R. prinoides* on farmlands with better soil depth for better growth and productivity while some farmers (32%) planted it on medium soil depth farmlands with additional treatments. Moreover, most farmers (97.8%) planted *R. prinoides* in the middle of the farmlands for better establishment and growth, and some farmers (32.8%) preferred planting on the farm sides for better growth and efficient land use.

Most farmers (79%) planted *R. prinoides* in a row (Figure 4.5c) while some of the farmers planted in a scattered (42%) (Figure 4.5a) and clone or block (13%) arrangement. Most farmers preferred a planting arrangement that enabled them to plant more trees/shrubs in a small farmland size because of their small landholding. As a result, scatter planting was a common practice among most of farmers while row planting becomes dominant these days because of its comparative advantages. From the practicing farmers, 52%, 42%, and 15.7% reported that they planted *R. prinoides* in a sparse, medium, and dense density, respectively. Most farmers were planting *R.*

prinoides densely assuming more harvest from more stems on small land while medium to sparse density planting becoming recognized nowadays for its better productivity.

Table 4. 6 *R. prinoides-based* agroforestry attributes and preference rank (1 for the least while 5 for the highest score values) and main reasons for the score given by practicing farmers (N=134).

Farming features	Farming attributes	Practicing (%)	Average score	Main reasons for score ranking
Plantation type	Sole planting	5.7	2.10^{a}	Best use of land, diversifying and maximizing products, better management and growth
	Inter-planting	100	4.11^{b}	
Intercropped crop types	Wheat	76.87	3.99^{a}	Resistant to shading effect, less damaged by birds, less competition for resources, fallowing or fertilizing effect,
	Beans	73.13	4.78^{b}	
	Maize	23.13	2.57^{c}	
	Barley	33.58	2.68^{c}	
Farm location	Homestead	98.5	4.73^{a}	Distance, better follow-up and management, better farm conditions,
	Field (Wefri)	28.4	2.42^{b}	
Farm condition (soil depth)	Deep soil (>1m)	84.3	4.79^{a}	Better soil moisture, better R. *prinoides* growth,
	Medium soil (0.5-1m)	32	3.59^{b}	
	Shallow soil (< 0.5m)	3.7	1.62^{c}	
Planting position	Middle farm	97.8	4.66^{a}	Better soil depth and moisture, land saving, better management, suitability for crops
	Farm boundary	34	2.46^{b}	
	Farm side	32.8	2.86^{c}	
Planting arrangement (layout)	Row planting	79.1	4.49^{a}	Land saving, better management, suitability for crops, better productivity
	Scatter planting	42.54	2.00^{b}	
	Clone planting	13.43	2.92^{c}	
Planting density	Dense	15.7	1.96^{a}	Land saving, better management, suitability for crops, better productivity
	Medium	47	3.54^{b}	
	Sparse	52.24	3.79^{b}	

Wilcoxon rank-sum test and Kruskal-Wallis test at 0.05 level and farming attributes within each farming feature with different superscripts along the column are significantly different.

4.3.4 Local Management Techniques of *R. prinoides-based* Agroforestry Practice

Different management systems were observed in *R. prinoides-based* agroforestry practice. Rain-fed *R. prinoides* inter-planting was extensively observed in the uplands while irrigation-based *R. pinoides* inter-planting was observed in the down-streams. Picking of matured *R. prinoides* leaves was the harvesting system in the Central, North-West, West, and Eastern zones of Tigray. *R. prinoides* shoots cutting after three to four years of rotation (coppicing) was the harvesting system in the South and most parts of the Southeastern zones of Tigray.

In the study sites, *R. prinoides-based* agroforestry practice by smallholder farmers had a significant share of their landholding (0.27 ha per household) with an average density of trees (540 trees per ha) for a prolonged period of cropping rotation (24 years on average) with varied performance

(Table 4.7). Most respondents (87%) indicated that the number of farmers practicing *R. prinoides-based* agroforestry and the share of the practice from the landholding of each household has increased over time. The land use share of *R. prinoides* agroforestry was 58.9% of the practicing farmers' landholding. As the area of the plantation increases the number of trees significantly increases while planting spacing negatively affects the number of trees on farmland (Table 4.8). Besides, as the planting spacing increases, the diameter at stump height (DSH), height, and crown diameter (CD) significantly increase. Moreover, as the age of the plantation and trees increases, the number of trees and leaves harvested increases.

Table 4. 7 Local management techniques of *R. priniodes*-based agroforestry practice and the growth performance of *R. prinoides*

Management techniques	Description	Mean	SD
Area of plantation (ha) per household	Farm size allotted for *R. prinoides-based* agroforestry per household	0.27	0.10
Spacing of planting (m)	Spacing among planted individual trees	3.04	0.89
Number of trees per household	Trees planted per household	97.67	74.15
Tree density (trees ha^{-1})	Number of trees planted per hectare	540.42	385.65
Age of a tree	The age of a tree since planted on a farm	18.79	11.58
Age of plantation	The age of a plantation since the establishment	23.95	7.87
Harvesting frequency	Harvesting frequency per tree in a year	2.71	0.46
DSH (cm)	Diameter at stump height of a tree	6.46	3.91
Height (m)	Total height of a tree	3.19	1.35
Number of shoots	Number of shoots per tree	3.86	1.89
CD (m)	The crown diameter of a tree	2.83	1.49
Leave harvest (kg tree^{-1} year^{-1})	Amount of leaves harvested from a tree in a year	3.18	4.26

Table 4. 8 The correlation of local management and the growth performance of *R. prinoides* trees/shrubs on cropland

Local management	Tree number	DSH	Height	Shoot number	CD	Leave harvest
Area of plantation	0.389**	0.048	0.034	0.148	0.035	-0.123
Spacing of planting	-0.105	0.237**	0.207*	0.097	0.294**	0.058
Tree density	0.765**	-0.043	-0.066	-0.152	-0.153	0.035
Age of trees	-0.067	0.728**	0.634**	0.232**	0.672**	0.509**
Age of plantation	-0.252**	0.114	0.148	0.044	0.204*	0.069
Harvesting frequency	-0.044	-0.038	-0.015	-0.068	-0.034	0.167

Pearson correlation analysis, **significant at 0.01 level, *significant at 0.05 level, DSH is the diameter at stump height, and the CD is the crown diameter.

Site selection, propagule selection, seedling production or purchasing, planting and tending, watering, guarding or fencing, and harvesting are some of the mentioned management techniques implemented in *R. prinoides-based* agroforestry (Table 4.9). Most management activities have different extents and temporal arrangements. The practicing farmers prefer farms with better soil conditions that are located near residences for *R. prinoides* plantation. Farmers prefer to produce seedlings by collecting seeds or seedlings from known mother trees/shrubs while some farmers used to purchase from private and communal nurseries. Composting, frequent cultivation, and supplementation of *R. prinoides* seedlings are required 3 to 4 years after planting, and follow-up (guarding or fencing) and harvesting are long-lasting activities. Besides, farmers indicated that as the age of the plantation increases the labor demand for harvesting increases while the labor demand for the other activities decreases.

All of the practicing farmers reported that careful partial picking of matured leaves to avoid new shoot damage in the dry season and complete harvesting of *R. prinoides* leaves before natural fall and budding begins in the rainy season is the harvesting system. *R. prinoides* leaves were harvested two to three times a year mainly in January, May, and August since the fourth year of planting following their morphological maturity before natural fall (shedding). Besides, proper drying of harvested leaves by putting on a flat and neat area supported by frequent steering upside-down on sunny days is required to maintain the quality of harvested leaves. Moreover, the properly dried *R. prinoides* leaf was required to be stored in a dry, ventilated, and clean warehouse to store it for longer periods. The harvesting times of *R. prinoides* leaves were different from the time of main farming activities. Most farmers (88%) reported that *R. prinoides* leaves harvesting is mainly accomplished by women.

Table 4. 9 Local management techniques practiced by all practicing farmers and requirements for better performance of *R. prinoides* plantations

Management activities	Measurement/indicators	Explanation
Farm selection	Better soil condition (depth and moisture), near residences	Better establishment, growth and follow-up
Propagation (Seed or seedling sources)	Mother tree with better growth and leaves phenology or nursery with better experience	Better growth and harvest, leave morphology suitable for harvesting and preferable in market
Planting care	50*30 cm pit preparation with 3 to 5 m spacing and arranged in a row	Better establishment, growth and management
Watering	Supplement watering in the dry season until 3 to 4 years after planting	Depending on rainfall patterns and soil moisture, watering at least once a month
Fencing or guarding	Strict fencing or guarding until 3 to 4 years and lasting reasonable follow-up	Protect from browsing animals and damage for better establishment, growth, and leaf harvest
Composting and cultivating	Frequent manual cultivation of root zone soil until 3 to 4 years	Improve soil condition (fertility and moisture) for better establishment and growth
Harvesting age	Mostly started since the 4th year of planting	Depending on the growth of the tree and the maturity of the leaves
Harvesting season	Dry season (mainly in January and May) and rain season (mainly in August)	Depends on the maturity of the leaves and the convenience of farm activities
Harvesting technique and care	Partial and careful picking of matured leaves only	To avoid damage of new shoots (lateral and apical dominances) to ensure continuous harvest of quality products (better market price and concentration)
Drying and storing	Exposing harvested leaves to sufficient sunlight and stocking them in a clean and dry warehouse	To reduce post-harvest losses and maintain the quality of products with better flavor (concentration) and market price

4.4 Discussions

4.4.1 Macro-distribution of *R. prinoides-based* Agroforestry Practice in Tigray

The MaxEnt model revealed that the distribution of *R. prinoides* agroforestry was predominantly influenced by temperature variables that accounted for 76% of the variation followed by precipitation which contributed 24%. The thermal effect was a more limiting factor than humidity on the distribution of *R. paranoids*-based agroforestry. Bioclimatic variables have significantly affected the distribution of *R. prinoides* agroforestry. Climate change could significantly change species distribution ranges (Broennimann et al. 2006; Chen et al. 2011). The contribution of anthropogenic factors could be important in the distribution of *R. prinoides* agroforestry, which was not considered in the distribution modeling.

The highlands and midlands, with moderate temperature and relatively better soil moisture, are potentially suitable for *R. prinoides*-based agroforestry practice. The ecological distribution of *R. prinoides* is from medium to high altitudes (Orwa et al. 2009). Likewise, Gebru et al. (2019) observed that different agroforestry systems have different agroecological niches in southern Tigray indicating that the type and extent of agroforestry in the highlands and lowlands significantly varied. The predicted results of the model showed that the future suitable agroecology for *R. prinoides* agroforestry in the 2050s and 2070s climate scenarios would decrease compared with the current climate scenario. However, comparing the two future climate scenarios, the areas with suitable agroecologies for the growth of *R. prinoides* were higher in the 2070s than in the 2050s. Similarly, Gallardo et al. (2015) reported that climate change is the main cause of the variation in habitat suitability. Besides, Ranjitkar et al. (2016) indicated that current and future climates have an impact on the agroforestry tree species distribution. Above all, human-induced factors such as the decision to practice, irrigation, and fertilization could play a significant role in the distribution variation of the practice.

Despite the presence of *R. prinoides* agroforestry in the midlands and highlands, significant differences in the extent of distribution and management system were observed. *R. prinoides* agroforestry was extensively observed in Ahferom, Ganta-Afeshum, and Medebay-Zana districts in Tigray. This might be attributed to the extent of the midlands and highlands suitable for *R. prinoides* growing, the difference in the culture of farming and the socioeconomic situation. Furthermore, Dalle et al. (2002) indicated that anthropogenic factors that include land-use dynamics could be more influential than natural factors in determining species distribution. In line with this, Gessesse et al. (2016) reported that tree-growing decision by local people is a function of a wide range of biophysical, institutional, socioeconomic, and household-level factors.

4.4.2 Micro-distribution of *R. prinoides*-based Agroforestry Practice

The extensive *R. prinoides* inter-planting in the uplands while limited to riverbanks or watersides in the lower altitudes could indicate that growing *R. prinoides* in the lowlands in rain-fed farming is constrained because of higher evapotranspiration and edaphic reasons. The higher abundance of

R. prinoides in the uplands might result because of better rainfall or moisture, moderate temperature, and lower evapotranspiration. The rain-fed *R. prinoides*-based agroforestry practice in aspects that received half-day sunlight indicated that *R. prinoides* grow better in areas with partial exposure to sunlight and lower evapotranspiration. The reason why *R. prinoides* mainly grow in the highlands as rain-fed might be because of more areas with mountains leeward from whole-day sunlight exposures which could have lower evapotranspiration. This coincides with the result of the MaxEnt model for macro-distribution and most farmers' observations of farmlands situated in areas with whole-day sunlight exposure are not suitable for *R. prinoides* planting. Likewise, Dalle et al. (2002) and Odeny et al. (2019) reported that elevation, aspect, slope, and drainage (upland, stream, and seasonal stream) determine agroforestry tree species distribution. Besides, Odeny et al. (2019) found climatic variables as strong determinants of species distribution in changing environments that resulted in higher tree species richness in the mountainous regions.

R. prinoides agroforestry is mainly found in farmlands with better soil depth in better abundance and growth performance. This indicates that *R. prinoides* requires farms with better soil conditions to establish and perform better. In line with this, most farmers indicated that farmlands with shallow soil depth are not good for *R. prinoides* planting because of their limited resource potential and root-supporting capacity. As a result, farmers used to allocate farms with better soil depth for *R. prinoides-based* agroforestry. The occurrence and abundance of *R. prinoides* increased in farms with lower bulk density. This might indicate that *R. prinodes* grow better in farms with silt loam soils which coincides with our observation on the soil texture in the uplands of the study site where *R. prinoides* plantations are found extensively. In addition to this, the distribution of *R. prinoides* increases in farms with better OC and K. Likewise, Russo et al. (2007) and Gue`ze et al. (2013) reported that edaphic variation that includes soil nutrient, soil texture, and soil depth determines tree species distribution. However, the higher OC and K in farms with higher *R. prinoides* abundance could be the result because of *R. prinoides* presence for years which might require further investigation.

R. prinoides agroforestry practices were mainly found in farmlands close to residences. The scattered settlements that were established mainly on the main landholding of the rural households in Tigray particularly in the study area may contributed to the higher *R. prinoides* agroforestry practice on farmlands close to residences. This might be a result because most of the residences were established around farmlands with better soil depth and farmers prefer planting *R. prinoides* around their residences for close follow-up and ease of management. As a result, farms nearby to residences could have better management inputs and protection from animal browsing and damage compared to farms located far from residences. Likewise, Gue`ze et al. (2013) reported that geographical distances and environmental variables explained 62% of the floristic variation for all trees. Above all, farms with similar microclimate and site selective conditions were observed with varied extents of *R. prinoides* agroforestry practice. This indicates that in addition to the biophysical factors, farmers' decision on their farms determines the micro-distribution of trees.

4.4.3 Nature and Arrangements of Components in *R. prinoides-based* Agroforestry Practice

The perennial trees/shrubs (*R. prinoides*) and the associated annual crops (wheat, bean, barley and maize) were the main components of *R. prinoides-based* agroforestry practice. This kind of diversity could lead to varied resource requirements, utilization zones and time, and production seasons that improve the efficiency of labor and farm resources utilization and sustainable production. *R. prinoides* was greener in the dry season while shedding its leaves in the rainy season (facilitated by harvesting). The inverse phenology (hydro-dormancy) of *R. prinoides* could make it less competitive and complementary with associated annual crops. Appropriate companion selection could improve resource utilization, component interaction and productivity of farming systems. Likewise, Teixeira et al. (2003) and Schroth et al. (2003) indicated that one of the tools that are available to a farmer for optimizing positive interaction among farm components is the selection of plant (and animal) species. The diverse choices of annual crops to be intercropped with *R. prinoides* among farmers could result from varied perceptions, experiences, and access of farmers. However, cowpeas and wheat were most preferable for cultivation in association with *R. prinoides* by most practicing farmers. Farmers' selection criteria for companion crops included farm fertility improving role, better resistance to birds' damage, shade tolerance, and less competition for resources with *R. prinoides*. This indicates that the indigenous and experiential knowledge of farmers plays an important role in companion crop selection. In line with this, Bukomeko et al. (2019) stated that companion selection in coffee agroforestry systems based on local knowledge enables to optimize delivery of ecosystem services that suit farmers' priorities.

R. prinoides planting layout and density were observed to play an important role in components interaction, land use efficiency, management suitability, and farm productivity. In line with this, Lasco et al. (2014) observed that agroforestry systems when well designed and properly managed, have some degree of beneficial effect on yield and income and potential for sustained production. Nowadays, row planting at medium density is becoming recognized by most farmers for optimized land use, convenient cultivation by oxen tracking, improved harvest from *R. prinoides,* and associated annual crops compared to densely scattered planting. The varied planting arrangement and density of *R. prinoides* agroforestry among farmers through time could result from varied choices and decisions of farmers that rely on their own production objectives, experiences, and perceptions. Likewise, Bukomeko et al. (2019) and Hamore and Lemage (2019) indicated that farmers have substantial and invaluable experiential knowledge about their farming systems.

The higher preference for farmlands nearby to residences for *R. prinoides* plantation could be because of the relatively lower management cost, and convenience for management and protection compared to farms far from residences. This indicates that farmers plant *R. prinoides* on farmlands at fields when farmlands at homesteads are not suitable for *R. prinoides* growing. Similarly, Gosling et al. (2021) found that labor demand and investment costs are determinants of selecting agroforestry in the forest frontier. Farms with better soil depth were selected for *R. prinoides* plantation because of their better soil moisture and root support compared to farms with shallow soil depth. Moreover, the higher preference of the middle part of farmlands for *R. prinoides* planting could be because the middle part of the farmlands is perceived to have better soil depth and moisture, lower moisture loss and lower exposure to animal damage compared to the boundary of farmlands. Likewise, van de Steeg et al. (2010) stated that the spatial distribution of farming systems is mainly determined by agro-climatic and socio-economic factors.

4.4.4 Local Management Techniques in *R. prinoides* Agroforestry Practice

Different management techniques were identified in different parts of Tigray which might be evolved because of the difference in experiential knowledge and perception toward the species, socioeconomic situation of communities, and biophysical conditions. The extensive practice of *R. prinoides* planting in rain-fed than in irrigation-based farming might be because of its higher comparative advantages in rain-fed farming or the limited irrigable lands. Furthermore, the widely practiced *R. prinoides* leaves harvesting system seems to be suitable for the rain-fed farming system compared to the coppice harvesting system. Above all, the differences in farming and harvesting systems might have evolved from biophysical and socioeconomic reasons which might require further investigations. Agroforestry tree management decisions are mainly related to farming systems, biophysical circumstances and tree characteristics, local knowledge and extension support (Madalcho and Tefera 2016).

Most farmers preferred farms with better soil conditions for *R. prinoides*-based agroforestry to intensify production which makes it different from agroforestry systems designed to reclaim degraded lands and reduce fertilization costs. Besides, most farmers prefer self-produced seedlings from known mother trees that phenotypically have better crown structure, larger leaf size, and better leaf arrangement for planting. Likewise, Sunwar et al. (2006) reported that farmers prefer self-established planting materials. Similarly, Gregorio et al. (2015) reported that improving the quality and supply of tree seedlings is crucial for the success of agroforestry, tree farming, and reforestation programs. This indicates that providing improved *R. prinoides* seedlings could improve farmers' productivity though there has not been any attempt so far. In addition to this, sparse planting (> 4 m) resulted in larger size of *R. prinoides* trees by crown diameter, total height, and DSH compared to dense planting (< 4 m) which could lead to better leaf harvest. This contradicts Gebremeskel et al. (2021) and Mabapa et al. (2017) report of higher biomass from dense plantations of *R. prinoides* on crop fields and *Moringa oleifera* on range land, respectively. However, according to farmers and our observation sparse planting was found to be with better *R. prinoides* growth with more foliage for harvesting and convenient for cultivation (oxen plough) and suitable for associated crops. Some farmers were even regretting planting dense though no one was willing to reduce the density of *R. prinoides* through thinning.

Watering seedlings in the dry season at least once a month, frequent cultivation and composting of seedlings' root zone soils, and fencing group or individual seedlings at least once a year are required until three to four years old for better establishment and growth of *R. prinoides* inter-planting in the rain-fed farming system. As a result, some farmers used to select farms around residences for planting *R. prinoides* for better follow-up and reduced fencing or guarding costs. Likewise, Madalcho and Tefera (2016) and Hamore and Lemage (2019) reported that farmers apply different management techniques for agroforestry trees that include fertilizing, watering, mulching, protection from animal damage, pruning, coppicing, thinning, pollarding for better establishment, reduce shading, regulate density, rejuvenation and improved productivity.

Proper *R. prinoides* leaf harvesting at three intervals in a year could enable farmers to attain sustained leaf harvest with better quality and quantity compared to coppice harvesting though it was found tedious and demanding. Likewise, Mabapa et al. (2017) reported higher leaf biomass production from four intervals of leaf harvest from *M. oleifera* plantation in a year. Furthermore, leaf harvesting throughout the year could enable farmers to utilize resources under climate variability (rainfall), bridging seasonal gaps, and reducing the shading effect on associated annual crops. This concurs with Bukomeco et al. (2019) and Lelamo (2021) observation that farmers select an agroforestry and management system that provides needed ecosystem services. Besides, both proper drying and storing of harvested *R. prinoides* leaves could help farmers to avoid or reduce post-harvest losses, bridging seasonal gaps of production and waiting for better market prices. Above all, despite being labor demanding, the varied periods of *R. prinoides* leaves harvesting from main farming activities could enable farmers to reduce peak and slack time which could help farmers to use their time and labor resources effectively. The increasing number of farmers practicing *R. prinoides-based* agroforestry and the expanding share of it in the land use system through time could be because farmers learning from their own and neighbors' experiences on its comparative advantages.

4.5 Conclusion

R. prinoides-based agroforestry is found in the highlands and midlands which are known for relatively better rainfall or moisture, moderate temperature and lower evapotranspiration. Temperature variables followed by precipitation were determinant factors in the prediction of *R. prinoides*-based agroforestry macro-distribution. Consequently, the future potential suitable agro-ecologies for *R. prinoides*-based agroforestry practice would be affected by climate change. The practice is a site-selective practice that was established on farmlands with partial or half-day sunlight exposure, and better soil depth and moisture and/or access to irrigation water. *R. prinoides*-based agroforestry is mainly rain-fed in the uplands while it is irrigation-based in the downstream. Above all, farmers' decisions on their farms play an important role in the distribution of *R. prinoides-based* agroforestry.

The mixture of *R. prinoides* and annul crops could reduce competition for resources and enhance complementarity among components because of varied resource requirements, utilization zones and time, and production seasons. Farmers prefer row planting of *R. prinoides* at medium density for convenience of cultivation, better component interaction and best use of space. Annual crops with better tolerance to shading effect and bird damage and less competition for resources that include cowpea and wheat were preferred by practicing farmers for cultivation in association with *R. prinoides* in rotation. Picking ripened leaves within three intervals in a year following morphological maturity of *R. prinoides* leaves is the harvesting system in the study area that enabled to improvement of the quality and quantity of leaf harvest, reduced the shading effect, utilized labor and farm resources throughout a year. The storability of properly dried *R. prinoides* leaves enables farmers to reduce post-harvest losses. Differed harvesting time of *R. prinoides* leaves from the main farming activities enabled farmers to best use of their time and labor resources and reduce peak and slack time problems. Thus, agroecological and land-use suitability analysis, farming system characterization and examining farmers' production objectives need to be prerequisites to scale up similar best practices.

Chapter 5 Socioeconomic Benefits of *Rhamnus prinoides*-based Agroforestry Practice to Smallholders in Tigray, Ethiopia[1]

5.1 Introduction

Developing countries mostly rely on agriculture for rural livelihoods and development. Nevertheless, several challenges such as population pressure, shortage of arable land, less improved farming practices, land degradation, uncertain market and climate change have resulted in reduced agricultural production and income (Mbow et al. 2014; Paul et al. 2017; Tian et al. 2021).While intensive agricultural systems have achieved relative success globally in terms of productivity (Keating et al. 2010; Krausmann et al. 2013), highly specialized farming practices (e.g., mono-cropping and high inputs) aimed at increasing economic efficiency and reducing production costs have led to less stable agricultural returns and increased sensitivity to exogenous factors (Falco and Chavas 2008; Kim et al. 2012; Abson et al. 2013; Dong 2020). A well-designed and properly managed diversified production system that integrates trees, crops, and animals is hypothesized to maximize and stabilize agricultural returns, sustain production, and reduce the risk of extreme events (Gockowski and Asten 2012; Mueller et al. 2012; Abson et al. 2013; Garnett et al. 2013; Lasco et al. 2014; Hernández-Morcillo et al. 2018). Accordingly, agroforestry is suggested as a global solution to increase land-use efficiency, while reducing environmental impacts and economic risks for farmers (Paul et al. 2017).

Agroforestry is increasingly recognized as a multifunctional agricultural practice, providing low input, indigenous, and resource-conserving farming approaches relevant options for rural development both socioeconomically and agro-ecologically (Koohafkan et al. 2012; Leakey 2012). It positively influences yield intensification drivers in Africa (Carsan et al. 2014). Diversified farming systems that incorporate agro-biodiversity (i.e. integrating trees/shrubs) are important for the sustainable intensification of agriculture through improved crop and land management (Gockowski and Asten 2012; Mueller et al. 2012; Garnett et al. 2013). Evidence

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shows that agroforestry systems provide greater stability and buffer against production and income fluctuations induced by uncertain or extreme events diversifying sources of products and income (Hernández-Morcillo et al. 2018). Moreover, agroforestry practices can provide an easily accessible, safe, and stable income, particularly benefiting women (Thorlakson and Neufeldt, 2012). *R. prinoides*-based agroforestry is extensively practiced particularly in the highland and midland of Ahferom and Ganta-Afeshum districts in Tigray providing diverse products and services. The leaves of *R. prinoides* trees/shrubs are widely harvested for making local alcoholic drinks called *Sewa* and *Mies* in the Tigrigna language. It has potential uses in the brewery industry as an ingredient that substitutes the commonly used hops (Andualem 2014), for natural dye extraction (Kechi et al. 2013), and ethno-medicinal uses (Alemu et al. 2007). This study aims to evaluate the role of *Rhamnus prinoides*-based agroforestry practice in increasing productivity, creating employment, generating income, empowering women, ensuring land use rights, enhancing social capital, and maintaining stable returns compared to annual crop mono-cropping among smallholder farmers in Ahferom and Ganta-Afeshum districts of Tigray, Ethiopia.

Despite the feasibility and benefits of agroforestry for smallholder farmers, evidence suggests that high production levels and economic values of agroforestry products could generate financial capital beyond subsistence levels (van Noordwijk et al. 2011; Thorlakson and Neufeldt 2012). Tesfay et al. (2024) reported higher financial returns from *R. prinoides* agroforestry than annual mono-cropping. However, the reasons for these better economic returns and the potential challenges and opportunities have not been thoroughly addressed. Moreover, financial return is only one of many other socioeconomic and biophysical factors determining an agroforestry practice's feasibility, acceptability, performance, and continuity (Franzel 2004; van Noordwijk et al. 2011). Profitability, household benefits, equity, sustainability, environmental services, markets for inputs and outputs, and institutions (property rights) influence the socio-ecological benefits of agroforestry (Alavalapati et al. 2001). Small landholding, outdated farming practices, and lower productivity characterizes the study area. Land degradation, market variability, and climate impacts lead to socioeconomic problems including food insecurity, unemployment, displacement, and migration in the area, exacerbated by increasing population pressure, rising food prices, and frequent war.

Despite efforts to improve productivity through imported technologies, the potential of local or indigenous best practices (agroforestry) to increase productivity, create employment, and maintain community, and their socioeconomic values have not yet been explored and evaluated. The lack of appreciation for the local or indigenous agroforestry practices can be attributed to an incomplete understanding of the role these practices currently play in food production, local economies, and ecological balance, or the potential of these systems for future agricultural development (Paul et al. 2017). The same is true about the socioeconomic significances and determinants of *R. prinoides-based* agroforestry while it is expanding in rain-fed and irrigated agriculture. Thus, a study on the motivation of practicing farmers, its role in the livelihoods of practicing farmers and local people, gender sensitivity, profitability and stability of returns, and socioeconomic and biophysical feasibility could enable us to understand the potentials of *R. prinoides* agroforestry and similar indigenous practices for sustainable agricultural development in smallholders farming.

Therefore, the objectives of this study were to (1) assess the purposes and socioeconomic implications of practicing *R. prinoides* agroforestry by smallholder farmers; (2) evaluate the gender roles associated with the practice; (3) determine the profitability of the practice compared to mono-cropping; and (4) examine the determinants of practicing *R. prinoides* agroforestry by smallholder farmers in Tigray, Ethiopia.

5.2 Methodology

5.2.1 Data Collection Method

A questionnaire with closed and open-ended questions was developed and improved after a pilot survey with 10 farmers. Primary data was collected through household surveys. Respondents were asked questions on the intended purposes of practicing *R. prinoides* agroforestry, its role in the livelihoods of practicing farmers and local people, land and tree use rights, sources of labor for the practice, social and ecological services of the practice, the role of females and males in planting, tending, harvesting, marketing and income management activities of the practice, costs incurred and benefits derived from the practice, and the driving factors of practicing *R. prinoides* agroforestry. Data on the costs and benefits of *R. priniodes* intercropping and wheat mono-cropping were collected from farmers with experiential knowledge. Costs and benefits were averaged on a hectare basis for the financial analysis. All the costs and prices were collected based on local market conditions or estimated based on data from farmers during data collection. The farm gate or local market prices for the *R. prinoides* and crop products were collected through interviews with both local sellers (farmers) and buyers in the local market.

Critical field observation was conducted on the spatial arrangement, farm size and condition, farm location, and abundance of the *R. prinoides* intercropping practice. Small to large farmlands with *R. prinoides* in the respective households were considered in the study and converted to hectares. The area of farmlands with *R. prinoides* was estimated using a GPS device while a complete trees/shrubs count was conducted. The *R. prinoides* trees/shrubs of each farm were stratified into three strata (small, medium, and large) based on height and crown sizes. Three trees/shrubs were randomly selected from each stratum. The minimum and maximum crown diameter (CD) (m), diameter at stump height (DSH) (cm), height (m), minimum and maximum spacing (m) to neighboring trees/shrubs, and shoot numbers on the sampled trees/shrubs were measured and counted. The average harvests from each selected *R. priniodes* at different size classes were estimated by recalling interviews of respective farmers. Key informant interviews were conducted with one agroforestry expert from each district, one extension agent and one local administrator from each village on the role of *R. prinoides* agroforestry in the livelihood of the local community and their role in the development of the practice. The information from key informant interviews served as guides for the field observation and a means for triangulation.

5.2.2 Analysis Methods

Qualitative and quantitative data analysis methods were used to analyze the collected data. Content analysis method and descriptive statistics were used to analyze the intended purposes of practicing *R. prinoide* agroforestry, and its socioeconomic implications and gender roles. The collected data were processed, and keywords or concepts were defined, categorized, coded, and summarized in frequency, means, and percentages. Interpretation was made based on the presences, patterns or trends, meanings or intentions, and relationships or implications of the concepts. The intentions of practicing farmers were examined to intensify production, commercialize farming and optimize incomes, diversify products and production season, stabilize production and income, bridge seasonal gaps, and accrue sociocultural and ecological services. The socioeconomic implications of the practice were evaluated based on its roles in the living means of practicing farmers and local people, income generation, employment opportunity, land,

and tree use rights and security, and enhancing social cohesions. The gender roles were assessed based on their level of engagement in planting, tending, product harvesting, product marketing, income administration, and labor market of the practice. The difference between female and male roles in *R. prinoides* agroforestry practice was analyzed using Chi-square test (X^2**).**

Financial returns and profitability of *R. prinoides* agroforestry were quantified based on information from farmers and the local market. The profitability of the *R. prinoides* intercropping practices was assessed based on specific enterprise budgets over the average production period of 30 years on a hectare basis. This is because the average productive lifespan of *R. prinoides* plantations was 30 years. Cost and benefit analysis was considered because it is a simple, powerful tool for comparing the profitability of alternative land uses and directly measurable financial elements (Klemperer 2003). A comparable method (Franzel et al. 2001) was applied to compare *R. prinoides* intercropping with wheat mono-cropping (staple crop in the study sites) and evaluate its financial return. The benefits and costs of *R. prinoides* intercropping practice were compared to the benefits and costs of wheat mono-cropping. The financial analyses were based on the costs and returns those farmers incurred and received throughout the production period of the practices. As land and labor were relevant resources for the farmers, the net returns to land and labor were calculated.

Average values for costs and returns across the sampled farmers were used to compute Net Present Value (NPV), Equivalent Annualized Income (EAI), Benefit-Cost Ratio (BCR) (Klemperer 2003), and Internal Rate of Return (IRR). The NPV, EAI, BCR, and IRR were used as decision criteria to compare the *R. prinoides* agroforestry practice with mono-cropping. To perform the NPV, EAI, and BCR, all costs and benefits of *R. prinoides* agroforestry and wheat mono-cropping practices were converted into the present values. This was done by discounting the costs and benefits that will be incurred in the future consecutive years. The following general formulas were used to discount cost and benefit streams which will be incurred in the coming years at different times.

$$Discounting\ of\ benefits = \frac{B_i}{(1+r)^n}\ and\ Discounting\ of\ costs = \frac{C_i}{(1+r)^n} \qquad (5.1)$$

Where, B_i stands for the- benefits earned at the ith year, C_i stands for the costs incurred at the ith year, n stands for the number of accounting years, and r stands for the real interest rate (%). A real interest rate accounts for inflation in the cost and benefit discounting flows. The real interest rate was calculated using the nominal interest and inflation rate data of recent consecutive years,

$$r = \frac{i-\pi}{1+\pi} \tag{5.2}$$

Where r is real interest rates (%), i is a nominal interest rate (%) and π is the inflation rate (Tilahun et al. 2007). The nominal interest rate was considered as an average of the lending and saving interests of the Ethiopian Banks. An average nominal interest rate *(i)* of 12.8% and an average inflation rate (π) 11.6 % were found for 2016 to 2020 based on data from the National Bank (NBE) and Central Statistics Agency (CSA) of Ethiopia. Accordingly, the real interest rate (%) was close to 1%. The initial investment cost and net cash flow in 30 years were used to compute IRR (%). IRR is the interest rate that gives an NPV equal to 0.

Sensitivity analysis was conducted to determine how changes in yield, prices, costs, and discounting rate would affect the financial analysis results. The basic assumption of the financial analysis includes constant yield, prices, costs, and discount rates. However, due to the fluctuation of yield, input costs, prices of outputs and discounting rates the profitability of the *R. prinoides* intercropping compared to wheat mono-cropping could be affected and uncertain for the future values. This is because the variability in production and market price is high in Ethiopia because of climate variability, conflict, and a high inflation rate. Hence, for the sensitivity analysis, a 50% decrease in yield and price of *R. prinoides* leaves and wheat grain, a 50% increase in fertilizer and seed cost, a 50% increase in wage rate, and a higher discounting rate (5%) were considered because of their significant share in the investment of the practices.

5.3 Results

5.3.1 Purpose of Practicing *R. prinoides*-based Agroforestry by Smallholder Farmers

The main purposes of practicing *R. prinoides* agroforestry by the smallholder farmers were to maximize the productivity of their small landholding (98.1%) and stabilize farm production (63%) against changing events (Table 5.1). Besides, smallholder farmers practiced *R. prinoides* agroforestry to maximize (100%) and stabilize (83%) farm incomes through farm product diversification. Most practicing farmers (75%) reported that the purpose of *R. prinoides* agroforestry was to reduce seasonality problems through cultivation and production season diversification (Table 5.1). The reason for *R. prinoides* intercropping as stated by practicing farmers (37%) was due to its minimal impact on farmland and associated crops, and its greening and microclimate amelioration roles (Table 5.1).

Table 5. 1 The main purposes of practicing *R. prinoides-based* agroforestry by smallholder farmers

R. prinoides AF main purposes	Response (%)	Justifications
Maximize farm production	98.1	Efficient resource utilization, increased annual production, and 2 to 3 times trees' product harvest in a year, higher labour requirement
Stabilization of farm production	63	Perennial and seasonal crops with varied nature of production and resource utilization time and horizons (niche)
Maximize farm income	100	*R. prinoides* products mainly for sale and increased farm product value
Stabilization of farm income	83	Products with commercial (non-food) and consumptive values, product diversification
Bridging seasonal gaps	75	Varied cultivation and harvesting time, diverse product harvest in the dry and wet seasons with varied values (commercial and consumptive), source of cash income for critical times
Sociocultural services	54	Improve social status (asset) and cohesion, tenure security (transfer and inheritance), funding ceremonies
Ecological services	37	Better soil fertility and moisture of the farm, minimal competition with most crops, ever greening and microclimate amelioration, inverse phenology of trees/shrubs

The key informants indicated that *R. prinoides* agroforestry practice is expanding by the motivation of the farmers in the study area. However, the roles of the agroforestry experts, extension agents, and local administrators in *R. prinoides* agroforestry practice have been minimal. The key informants indicated that government agents did not support or discourage *R. prinoides* planting by farmers. As government agents, the key informants indicated two possible reasons for the minimal attention and intervention. First, the practice is assumed to be well practiced by farmers. Second, the product that *R. prinoides* trees/shrubs provide is nonfood.

5.3.2 Socioeconomic Implication of *R. prinoides-based* Agroforestry Practice

R. prinoides-based agroforestry had a significant socioeconomic impact on 70.9% of farmers, deemed important by 24.6% and less significant by 4.5% of those engaged in this practice. The number of *R. prinoides* trees owned was not enough for the practicing farmers (90.3%). Most practicing farmers (91%) had planned to plant more trees to gain more benefits, replace old, poor and dried ones, and transfer them to their children, while few farmers (8.95%) did not have plans to plant additional trees/shrubs because of their old ages and limited suitable land for *R. prinoides* planting.

The primary objective of planting *R. prinoides* was to produce *R. prinoides* leaves for sale. *R. prinoides* products were sold at local towns (75.4%), farm gates (37.3%), and cities far from the locality (13.4%) with slight price differences. Most practicing farmers (81%) obtained their cash income from the *R. prinoides* leaf harvest sales followed by sales from livestock and crop products, and wage labor, respectively. Some farmers (47%) locally barter R. *prinoides* products and transport them to areas that do not practice *R. prinoides* planting.

The practicing farmers (54%) indicated that planting *R. prinoides* trees/shrubs was important to secure land use rights as a permanent marker for continuous farm uses and claiming compensation for the trees' product values. The sources of labor for practicing farmers were family labor (98.1%), exchange labor (43.4%) and daily labor (35.8%). All practicing farmers use *R. prinoides* products as an ingredient to make local alcoholic drinks that are locally called *Sewa* and *Mies*. Some practicing farmers (15.1%) shared *R. prinoides* products with their relatives, friends, and neighbors as an in-kind gift.

The key informants stated that *R. prinoides* agroforestry plays a significant role in the socio-economy of the local people. The areas are known for producing quality *R. prinoides* products in Tigray, Ethiopia. The key informants stated that even though the attention and support required to its contribution is low the existing practice has benefited the community as producers, laborers, and traders. The key informants applaud studies that provide evidence of the practice's socioeconomic and ecological importance and draw the attention of policymakers and development agents.

5.3.3 Gender Roles in *R. prinoides-based* Agroforestry Practice

The role of males was higher than females in planting and tending activities while the role of females was higher than males in harvesting *R. prinoides* leaves which requires a higher labor investment (Table 5.2). According to the practicing farmers' perception, the main reasons for the higher role of females in *R. prinoides* leaves harvesting were because females are better than males in picking the leaves (59.7%), labor division (33.5%) and tradition (20.9%). In *R. prinoides* product marketing, females held a greater role than males, whereas in *R. prinoides* product bartering outside their local area, males had a higher role than females (Table 5.2). Furthermore, women have a more significant role than men in managing the income generated from selling *R. prinoides* products. Females have dominantly participated in labor exchange specific to *R. prinoides* leaf harvesting (Table 5.2). For instance, exchanging a man's or an ox's labor to plow farmland with a woman's labor to harvest *R. prinoides* leaves for a day is common practice. In addition, females have dominantly participated as daily laborers in *R. prinoides* leaf harvesting.

Table 5. 2 Gender role in different activities of *R. prinoides-based* agroforestry practices

Agroforestry Activities	Gender role or participation		Difference (% point)	Significance X^2 (P-value)
	Female (% yes)	Male (% yes)		
Planting	35.8	79.1	-43.3	0.000
Tending activities	49.3	77.6	-28.3	0.000
Harvesting	96.3	11.9	84.4	0.000
Exchange in-kind	27.6	47.0	-19.4	0.001
Marketing of product	70.9	39.6	31.3	0.000
Income administration	72.4	39.6	32.8	0.000
Daily Labor	40.3	8.2	32.1	0.000
Exchange of Labor	47.8	10.4	37.4	0.000

5.3.4 Profitability of *R. prinoides-based* Agroforestry Practice by Smallholder Farmers

Farm plots with *R. prinoides* intercropping were more productive and profitable than mono-cropping according to 91.8% of farmers practicing *R. prinoides-based* agroforestry. However, a financial analysis was required to prove whether farm plots with *R. prinoides* agroforestry were more profitable than annual mono-cropping. Producing or purchasing tree seedlings, reduced wheat yields, fencing, watering seedlings, and labor for harvesting leaves were the additional costs involved in *R. prinoides* agroforestry, relative to wheat mono-cropping. The cost of purchasing wheat seed and fertilizer was similar in both farming systems. Labor used in the *R. prinoides* agroforestry over a 30-year rotation was around 2 times higher than wheat mono-cropping, primarily because *R. prinoides* harvesting accounts for around half of the total labor required. The advantage of *R. prinoides* agroforestry was that farmers earned positive net benefits throughout the rotation. The waiting time to start *R. prinoides* leaf harvesting was 3 years from planting. The *R. prinoides* leaves produce and harvesting labor requirement increases while the associated wheat harvest decreases, proportionally until tree growth reaches the optimum stage.

R. prinoides-based agroforestry enabled practicing farmers to earn USD 2,721 $ha^{-1}year^{-1}$ more than wheat mono-cropping (Table 5.3). The return to land in net present value (NPV) of *R. prinoides* agroforestry was USD 113607.80 ha^{-1}, over 3 times higher than wheat mono-cropping (Table 5.3). The agroforestry's return to labor, expressed in discounted net benefits per discounted workday, was USD 18.05, over 80% higher than wheat mono-cropping. The benefit-cost ratio of *R. prinoides* agroforestry was 75% higher than wheat mono-cropping. Moreover, the annual growth of capital of *R. prinoides* agroforestry was higher than wheat mono-cropping by 12% (Table 5.3). The internal rate of return from *R. prinoides* agroforestry (39%) and wheat mono-cropping (27%) was higher than the adjusted or real interest rate (1%) and nominal saving interest rate (7%) in banks.

Table 5. 3 Comparisons of financial returns from *R. prinoides-based* agroforestry and wheat mono-cropping.

Benefit and costs	*R. prinoides* agroforestry	Wheat mono-cropping
Wheat yield over 30 years (ton ha^{-1})	37.23	45.00
R. prinoides leaves yield over 30 years (ton ha^{-1})	68.10	-
Workdays per ha over 30 years	8,061.50	4,320.00
Discounted net benefit to labor (USD)	128587.30	40062.98
Return to Labor: DNR (USD $workday^{-1}$)	18.05	10.41
Return to land: NPV (USD ha^{-1})	113607.80	31970.10
Annuity income (EAI) (USD $ha^{-1}year^{-1}$)	4249.34	1195.80
Benefit-cost ratio (BCR)	6.17	3.54

DNR is discounted net returns, NPV is net present value, and USD is United States Dollar

Sensitivity analysis showed that the performance of *R. prinoides* agroforestry relative to wheat mono-cropping was stable across a wide range of changes (Table 5.4). Decreases in the yield or price of *R. prinoides* leaves or wheat products and increases in wage rate and higher discount rate did not affect the superiority of *R. prinoides* agroforestry against wheat mono-cropping. Among the key parameters examined, the profitability of *R. prinoides* agroforestry was most sensitive to the decrease in the *R. prinoides* product price and yield and the increase in the discount rate. The profitability of the wheat mono-cropping was sensitive to decreases in wheat price and yield, and an increase in wage rate.

Table 5. 4 Sensitivity analysis for *R. prinoides-based* agroforestry and wheat mono-cropping

	R. prinoides agroforestry				Wheat mono-cropping			
Key parameters	DNR	NPV	EAI	BCR	DNR	NPV	EAI	BCR
Base analysis	18.05	113607.80	4249.34	6.17	10.41	31970.10	1195.80	3.54
50% decrease in *R. prinoides* yield or price	11.18	64673.93	2419.04	3.94	10.41	31970.10	1195.80	3.54
50% decrease in Wheat yield or price	16.01	99096.23	3706.55	5.51	5.87	14507.78	542.64	2.15
50% increase in fertilizer cost or use	17.89	112523.90	4208.80	5.88	10.13	30886.23	1155.26	3.26
50% increase in seed cost	17.88	112443.70	4205.79	5.86	10.10	30805.94	1152.252	3.24
50% increase wage rate	18.05	106118.10	3969.20	4.60	10.41	27923.66	1044.44	2.68
5% discount rate	17.03	58261.52	2179.19	5.84	10.41	18382.31	687.56	3.54

5.3.5 Determinants of Practicing *R. prinoides-based* Agroforestry by Smallholder Farmers

Gender, age, family size, land ownership, farm size, farm fertility, number of farm parcels and wealth status were significant determinants of practicing *R. prinoides* agroforestry, farmland size allotted to the practice, the number of *R. prinoides* trees to be planted and the planting density (Table 5.5). Male-headed households are more likely to practice *R. prinoides* agroforestry by planting more *R. prinoides* trees in higher density than female-headed households. Older household heads are more likely to practice *R. prinoides* agroforestry by allocating larger farmland. Households with larger units of family size are more likely to allocate smaller farmland and plant fewer *R. prinoides* trees.

Younger farmers who share their parents' farmland practice less *R. prinoides* agroforestry and plant fewer trees in lower density than farmers who own farmlands. Households that own larger farms are more likely to practice *R. prinoides* agroforestry by planting more trees in larger farmland areas. Farmers having farmlands with poor fertility are more likely to practice less *R. prinoides* agroforestry by allocating smaller land for planting fewer trees in lower density than farmers with fertile land. Farmers with higher units of farm parcels are likely to practice less *R. prinoides* agroforestry and plant fewer trees in lower density than farmers with consolidated farmlands. Households with relatively middle income are more likely to practice *R. prinoides* agroforestry while those with lower income are likely to plant fewer trees than households with higher income.

Table 5.5 Determinants of planting, and number, area and density of *R. prinoides* trees planted by smallholder farmers

Factors	Practicing *R. prinoides* AF (glm, binomial)	Number of *R. prinoides* trees hh^{-1} (glm, quasipoison)	*R. prinoides* AF area (ha) (lm)	Tree density (trees ha^{-1}) (glm, quasipoison)
Gender (1if male)	1.08(0.56)*	0.37(0.22)*	0.022(0.03)	0.35(0.20)*
Age	0.09(0.03)***	0.002(0.01)	0.003(0.002)*	0.001(0.01)
Education (years)	-0.04(0.10)	0.003(0.04)	-0.004(0.005)	-0.004(0.04)
Family size (count)	-0.12(0.14)	-0.14(0.05)**	-0.015(0.01)**	-0.069(0.05)
Land ownership (1 if parent)	-2.18(0.84)***	-0.68(0.35)*	-0.042(0.041)	-1.06(0.39)***
Farm size (ha)	6.64(2.29)***	1.29(0.64)**	0.21(0.10)**	0.999(0.63)
Farm fertility (1 if medium)	-0.84(0.53)	-0.25(0.17)	-0.04(0.027)	-0.20(0.16)
Farm fertility (2 if shallow)	-3.23(0.85)***	-1.59(0.57)***	-0.15(0.044)***	-1.33(0.48)***
Farm parcels (count)	-1.31(0.39)***	-0.23(0.13)*	-0.007(0.019)	-0.39(0.13)***
Wealth status (1 if middle income)	1.93(1.03)*	-0.20(0.34)	0.055(0.055)	-0.17(0.32)
Wealth status (2 if low income)	0.17(1.02)	-0.72(0.37)**	-0.03(0.058)	-0.46(0.35)
Climate awareness (1 if yes)	0.05(0.77)	0.41(0.31)	0.016(0.04)	0.49(0.31)
Model fitness (R^2)	0.46	0.25	0.27	0.24

*Significant at 0.1 level, **significant at 0.05 level, ***significant at 0.01 level, AF is agroforestry, hh is household, ha is hectare, glm is a general linear model and lm is a linear model

5.4 Discussion

5.4.1 Purposes of practicing *R. prinoides-based* agroforestry

R. prinoides-based agroforestry has been serving as a means for sustainable yield intensification and optimization of household income. The transition from seasonal farming to perennials and annual multi-cropping requires a more intensive and larger workforce. Integrating annuals and perennials in the farming systems increases the productivity of both labor and farmland. The different species integrated in the practice support productivity at various times and spread the labor requirements (Isbell et al. 2011). As a result, farmers utilize their labor more efficiently, reducing periods of slack and peak labor season. Likewise, Soren (2007) reported that smallholders increase their labor efforts to increase land productivity by cultivating labor-intensive commercial crops to supply their survival needs. The commercial product of *R. prinoides* agroforestry maximizes the farm income. This indicates that profit maximization may not be achieved automatically from the maximization of yields but from the diversification of products with higher market value. In agreement with this finding Verchot et al. (2007) reported that tree-based production systems often produce products of higher values than farming with annual crops. Besides, many studies stated the importance of integrating trees in land use systems for the sustainable intensification of agricultural production using natural processes to achieve desired yield through improved crop and land management (Gockowski and Asten 2012; Garnett et al. 2013; Mueller et al. 2012).

R. prinoides agroforestry plays a role in stabilizing production and income against changing events. The integration of *R. prinoides* trees /shrubs in crop fields enhances the stability of farm returns. Different studies reported that practices involving species mixtures in diversified production systems are productive, resilient, and sustainable (Leakey 2012; Dawson 2013; Carsan et al. 2014). This is because the trees/shrubs component of the practice increases farmland and labor use efficiency, reduces environmental impacts, and buffers against production and income risks (Verchot et al. 2007; Paul et al. 2017). *R. prinoides* agroforestry provides commercial and consumptive products from the trees/shrubs and associated annual crops, in varied periods. This finding coincides with Duffy et al. (2021) report that agroforestry plays a key role in stabilizing the income of households in Indonesia because of the year-round availability of its products. Agroforestry systems can provide staples and marketable tree products to improve livelihoods (Leakey 2012; Dawson, 2013) and may buffer against production and income risks (Verchot et al. 2007; Cubbage et al. 2012). Similarly, Olson et al. (2000) and Berman et al. (2015) reported that incorporating perennial plants into farming provides greater resiliency to inter-annual variability through diversification of products and production season and increased resource-use efficiency.

The seasonal complementarity in *R. prinoides* agroforestry is characterized by the mixture of perennial trees and annual crops which are cultivated, grown, produced and harvested in varied periods and seasons that lead to the distribution of farm and labor resource requirements and income generation in a year. This could enable farmers to avoid labor peak season and bridge seasonal income shortfalls. The storability of *R. prinoides* leaves in clean and dry warehouses for at least a year could also reduce seasonality problems resulting in low prices at peak harvesting seasons. These findings align with Gill (1991) statement that trees formed the basis of counter-seasonal strategies in combination with arable crops and livestock and tree products. Spreading production throughout the year benefits farmers through more efficient land, labor, and capital use, and get regular and stable income (van Noordwijk et al. 2011).

The better soil condition on farmlands with *R. prinoide* trees/shrubs could be because of the trees/shrubs' role in enhancing soil moisture, water use efficiency and maintaining soil fertility (Gebremeskel et al. 2017). This could be attributed to the continuous cover, litterfall, soil stabilization and microclimate amelioration roles of the trees/shrubs. Similarly, Donald (2004) and Cardinale et al. (2011) observed that farm crop diversity contributes to ecological intensification. Some environmental services of *R. prinoides* agroforestry are increased carbon sequestration and storage (Gebremeskel et al. 2021), and biodiversity conservation seems to be an unintended outcome of the practice.

5.4.2 Socioeconomic Implication of *R. prinoides-based* Agroforestry Practice

The noteworthy socioeconomic impacts of *R. prinoides* agroforestry on practicing farmers are ascribed to the scale and longevity of their engagement in *R. prinoides* agroforestry and its contribution to their means of living. Specifically, *R. prinoides* agroforestry benefits more to farmers who own smaller farmlands, and with lower incomes than farmers with larger farmlands and higher incomes. This coincides with Deressa et al. (2009) who reported that larger farm size is associated with greater wealth in Ethiopia.

Farmers planted *R. prinoides* trees/shrubs mainly to harvest their leaves for commercial purposes. The commercial product of the trees enables smallholder farmers to transform from consumptive-based to semi-market-oriented farming. This indicated the possibility to transform subsistence farmers from consumptive-based to a market-oriented production system. This aligns with Verchot et al. (2007) report of higher-value products from tree-based production system. Soren (2007) argues that commercializing subsistence farming requires a change of mindset by farmers, the existence of a market and an enabling economic environment. However, most practicing farmers reported that inter and intra-annual price variability was the challenge of the production system. Although the farm-gate price is relatively low, it was considered a comparative advantage by some farmers with difficulty transporting far from their vicinity, such as women with kids and older ones.

Farmers indicated that the income from *R. prinoides* products sale plays a significant role in improving their livelihood. Farmers used the cash income from *R. prinoides* sales to purchase different household food supplements, clothing, educational materials, furniture (bed), utensils (kitchen and farming tools), and housing materials (iron sheets and cement). The income from *R. prinoides* product sale was an important source of savings for farmers investing in other productive livelihood strategies such as farm inputs (seed and fertilizer), livestock and livestock feeds, poultry, and beehives. Likewise, some studies indicated that income from agroforestry products sale could enable farmers to accumulate capital that can be reinvested in farming activities because tree/shrub products may generate financial capital beyond subsistence levels (van Noordwijk et al. 2011; Thorlakson and Neufeldt 2012; Duffy et al. 2021).

R. prinoides product was a business commodity for retailers, exporters, and local beer brewers. Hence, *R. prinoides* agroforestry is the source of employment and income for the locals and nearby people other than the farmers cultivating it. In addition, the practice could improve the linkage between urban and rural communities, and the networking of farming and businesspeople. This indicates that *R. prinoides* agroforestry has a multiplier effect beyond its practicing community. Likewise, Duffy et al. (2021) reported that agroforestry systems with a commercial focus could contribute up to five times more income in Indonesia.

The tenure system in Tigray and Ethiopia rewards farmland use rights and ownership of planted trees. Farmers can transfer their ownership of *R. prinoides* trees to their children when they get married. Besides, farmers can bequeath their *R. prinoides* trees to their children when they get old. These could be additional social incentives to plant more *R. prinoides* trees by farmers. Similarly, Fortmann (1985) stated that agroforestry development depends on people’s right to plant and use trees, and the land and tree tenure system in Africa. Besides, Duffy et al. (2021) reported that establishing trees confers land tenure security in Indonesia.

Besides self-employment, farmers practicing *R. prinoides-based* agroforestry employ community members during the off-farm seasons and facilitate social networking. This is because the harvesting time of *R. prinoides* product was mainly on the off-farming season. As a result, labor allotted to non-farming activity and leisure time was low among households practicing *R. prinoides* agroforestry. Underemployment was minimal and labor productivity was relatively better in households practicing *R. prinoides* agroforestry although highly affected by market price variability. This finding concurs with the observation of Isbell (2011), van Noordwijk et al. (2011) and Paul et al. (2017) that tree/shrub components in farming systems increase farmland and labor use efficiency, and buffer against both production and income risks by spreading production throughout a year.

The commercial value of *R. prinoides* products evolved because of the local breweries that use *R. prinoides* leaves as an ingredient. The local beers are important for home consumption in peak farming times, holy days, ceremonial activities such as baptizing and weddings in Tigray and Ethiopia. For the practicing farmers, the cash income from *R. prinoides* product sales was also important to purchase some materials required to undertake those social and traditional activities and ceremonies. Sharing *R. prinoides* products as an in-kind gift at special events to people in urban and rural areas who do not practice *R. prinoides* agroforestry enables them to improve their social linkages.

Generally, *R. prinoides-based* agroforestry maximizes social capital and income that enhances the socioeconomic well-being of the local people. These enable it to play great roles in community conservation by maintaining viable rural populations that sustain their culture, tradition, and social cohesion. Similarly, Leakey (2012) claims that agroforestry provides low input and resource-conserving farming approaches that are socially relevant for rural development. Commercializing agroforestry products incentivizes subsistence farmers to plant trees to reduce poverty and enhance food and nutritional security, human health and environmental sustainability (Garrity 2004; Duffy et al. 2021).

5.4.3 Gender Roles in *R. prinoides* Agroforestry Practice

Despite the shared responsibility of household members in the *R. prinoides*-based agroforestry, the roles of females and males differed in different activities. The higher role of males in planting and tending activities could be because the household heads are males who decide the number of trees to be planted and where to be planted in the farmland. Watering seedlings was a shared responsibility among the female and male members of the household while fencing was mainly the responsibility of males. The higher role of females in *R. prinoides* leaves harvesting is because of the established cultural division of responsibility between females and males based on perceived reasons. For instance, females are believed to be better than males in harvesting the leaves of *R. prinoides*. The different gender roles coincide with Kiptot and Franzel's (2012) report on different gender roles in agroforestry management that are skewed toward women in Africa. Most of the perceived labor division seems convincing, although it needs to be improved. They argue that when males do not have other overlapping and productive activities, *R. prinoides* harvesting should be the shared responsibility of both female and male household members.

The increased involvement of females in *R. priniodes* product marketing and income administration may be attributed to their greater role in leaf harvesting. The concept of labor creates right, as proposed by Volker and Waibel (2010) can be applied to explain the heightened role of women in overseeing the income generated from the sale of *R. prinoides* products, owing to their substantial labor investment in the overall management of *R. prinoides* agroforestry. By actively participating in income-generating activities and assuming a greater role in income administration, women can enhance their influence within their households and communities. This finding is against Kiptot and Franzel (2012) report of lower women participation in marketing and managing returns from agroforestry with commercial value in Africa. The higher role of males in exchanging *R. prinoides* products in-kind could be because it requires traveling far from the locality for a prolonged time which is inconvenient for females with higher responsibility of household care. The dominant participation of females as daily and exchange laborers specifically in *R. prinoides* harvesting was because females are believed to be better than males in *R. prinoides* product harvesting. These could be considered as employment and income-generating opportunities created by *R. prinoides* agroforestry for women in their locality.

The significant role of women in *R. prinoides* agroforestry practice up to income administration could make women economically benefited and socially empowered. This coincides with Thorlakson and Neufeldt (2012) claim that trees on farms provided a more accessible, safe and stable source of income, particularly benefiting women. The higher role of women in *R. prinoides* agroforestry management could be because of their better performance and local labor division. In agreement with this finding, Cecelski (2000) indicated that men and women in many developing countries assume different roles in livelihood activities often with unequal share. Consequently, Oglethorpe and Gelman (2008) suggest a proportional share of livelihood activities as a mechanism to improve the living conditions of women. However, the higher role of women in *R. prinoides* agroforestry management might create a labor burden and affect their role in other activities. Thus, a comprehensive investigation of the role of gender in the livelihood activities of households might be required to evaluate the management and share of women's labor and time.

5.4.4 Profitability of *R. prinoides-based* agroforestry practice

The return to land (NPV) of *R. prinoides* agroforestry was threefold compared to wheat mono-cropping. This result could be because integrating *R. prinoides* trees/shrubs and annual crops intensifies the use of farm and labor resources providing commercial and consumptive value products. Trees/shrubs (perennial) based farming requires a long time to reach its optimum production level. The low real interest rate (1%) in Ethiopia resulting from a high inflation rate is favorable for farming systems that incorporate perennials with a 30 years production period. This agrees with Lasco et al. (2014) who reported that when agroforestry systems are well-designed and properly managed, they enhance yield, income, and potential for sustained production. Returns to labor are also relevant to farmers, because of the opportunity costs of labor. The higher return (over 80%) to the labor of the *R. prinoides* agroforestry is due to the maximization of income through commercializing farming compared to wheat mono-cropping. The labor required for harvesting the *R. prinoides* leaves was significant and spread during the farmers' off-farming season. The higher benefit-cost ratio (75%) of the *R. prinoides* agroforestry indicates lower input costs or higher return to inputs of the practice compared to wheat mono-cropping. This finding aligns with Koohafkan et al. (2012) report that some forms of agroforestry require low external inputs and have a high recycling rate. This can be further enhanced through better farming and improved tree and crop variety (Garrity 2004; Leakey 2012).

The maximized and stabilized production and income through component and product diversification brought a stable *R. prinoides* agroforestry performance relative to wheat mono-cropping. *R. prinoides* agroforestry profitability was sensitive to *R. prinoides* product price and yield decrease and increase in the discount rate. The sensitivity is due to the higher yield and income from *R. prinoides* than the associated crop and the low real discount rate (close to 1%) because *R. prinoides* plantations require a longer time to reach an optimum level of production. These findings align with van Noordwijk et al. (2011) report of more regular and stable income from trees/shrubs-based farming systems. *R. prinoides* agroforestry was labor intensive compared to wheat mono-cropping. Reducing labor costs was an important aspect of increasing profitability in the systems. Enhancing the productivity of labor in the *R. prinoides* agroforestry requires improved methods of cultivation and harvesting systems. The harvesting time of *R. prinoides* products was mainly in the off-farm season. The staggered harvesting time of *R. prinoides* and annual crops enables farmers to reduce labor peak and slack times throughout the year. Farming systems integrating trees/shrubs spread labor requirements (Isbell 2011). However, with time, labor could constrain the farming system's productivity. Labor is the major factor of production (Volker and Waibel 2010). Accordingly, farmers' labor allocation to *R. prinoides* harvesting varies with its market price.

The price of *R. prinoides* products varies seasonally and annually. This has been neutralized because of the storability of the product for a reasonable time. Agricultural product prices fluctuate more than other prices when supply and demand change (Soren 2007). Subsistence farmers were reluctant to specialize in nonfood production to reduce the risk of market failure. Increased agricultural productivity and stable and expected market price could reduce the risk of turning from subsistence farming to commercial farming of nonfood production. The shift in consumption from local alcoholic drinks that use *R. prinoides* leaves as an ingredient to brewery drinks will be a critical challenge to the stability of market prices and the future of the farming system. Hence, it is important to look for mechanisms either to use *R. prinoides* leaves as an ingredient by the brewery industries or alternative farming with similar agroecological and socioeconomic values for the community.

The higher annual income and capital growth from *R. prinoides* agroforestry conforms to Duguma (2012) report that agroforestry practices are financially advantageous compared to the annual crop mono-cropping. Besides, this finding supports the argument of van Noordwijk et al. (2011) and Thorlakson and Neufeldt (2012) that agroforestry products could generate financial capital beyond subsistence levels. Furthermore, the higher internal rate of return from *R. prinoides* agroforestry and wheat mono-cropping than the saving interest rate indicates that the gain from agricultural investment is profitable and stable. Sociocultural and ecological services are additional intangible benefits of the system. For example, *R. prinoides* trees serve as permanent markers to ensure farm use-right, microclimate amelioration, improve soil structure and moisture retention, reduce soil erosion, sequester carbon (Gebremskel et al. 2017; Gebremeskel et al. 2021) and provide firewood.

Credit for establishing *R. prinoides* agroforestry was not required for smallholders. Production starts on a small scale and gradually increases the areas they allocate to the practices. The payback period of the practice was also relatively short. To improve the profitability of smallholders, emphasis should be given to increasing farm and labor productivity through farmer-based research and innovations in the cultivation and harvesting systems of the practice. Moreover, the improvement of market efficiency and business opportunities through targeted marketing strategies are meant to improve the profitability of agroforestry.

The profitability analysis presented emphasizes enterprise-specific budgets which may miss important interactions among enterprises within the farming household. Analyses of profitability should not be considered the sole criterion for assessing the feasibility, acceptability, and adoption potential of an agroforestry practice to farmers (Franzel et al. 2001). Profitability is certainly an important criterion but other factors such as cultural taboos, farmer preferences, resource bottlenecks, policy constraints, and market failures also play important roles. For instance, we observed that *R. prinoides* planting is prohibited among Muslim farmers. In addition to this, *R. prinoides* agroforestry is sensitive to market failure because of its product being nonfood compared to mono-cropping with food products. Hence, assessments of profitability need to be complemented by other types of studies to identify and assess these and other issues that farmers face in using agroforestry practices.

5.4.5 Determinants of Practicing *R. prinoides-based* Agroforestry

Agricultural performance depends on the willingness and ability of the farmers to make the right decision at the right time. Benefit, enabling biophysical and socioeconomic environment and knowledge could play a greater role in determining the practicing of certain farming systems than others. Male-headed farmers practice *R. prinoides* agroforestry by planting more *R. prinoides* trees in higher density than female-headed households because males-headed households have more labor and the decision to transition from an annual-based to a perennial-based farming system. Similarly, to this result, Deressa et al. (2010) concluded that male-headed households are more likely to embrace alternatives and take risky businesses than female-headed households because of their access to information about existing environmental conditions and alternative technologies. Older farmers allocated larger farmland to *R. prinoides* agroforestry as they own relatively larger farm sizes and more farming experiences. In agreement with this result, several studies have shown a positive relationship between years of experience in agricultural activities and the implementation of improved technologies (Maddison 2006; Deressa et al. 2009; Gyau et al. 2015).

The likelihood of allocating smaller farmland and planting fewer *R. prinoides* trees by households with larger units of family size is contrary to the expectation. This finding is also contrary to

Croppenstedt et al. (2003) and Beyene et al. (2019) report that households with a larger pool of labor are more likely to implement various agricultural technologies and use them more intensively in on-farm and off-farm activities. However, this study considered the total family size and has the limitation in stratifying the productive and non-productive members of the family. The likelihood of less practicing *R. prinoides* agroforestry and planting fewer trees in lower density by farmers relying on parents' farmland indicates that land tenure security is an important factor in practicing perennial farming systems. Farmers with secure tenure were more likely to adopt long-lasting technologies in Africa (Gbetibouo et al. 2010; Fosu-Mensah et al. 2012).

The greater likelihood of practicing *R. prinoides* agroforestry by planting more trees in larger farmland areas by households with relatively larger landholding indicates that slight differences could affect farmers' adoption of different farming systems and technologies. Beyene et al (2019) reported that farmers with larger land sizes practice agroforestry with higher intensity while Deressa et al. (2009) indicated that larger farm size is associated with greater wealth. The higher probability of practicing *R. prinoides* agroforestry by allocating larger farmland for planting more trees in higher density by farmers having fertile farmlands compared to farmers having farmlands with poor fertility indicates that *R. prinoides* planting requires fertile lands. Soil fertility has a positive effect on the use of best practices in Africa (Fosu-Mensah et al. 2012). The lower likelihood of practicing *R. prinoides* agroforestry and planting fewer trees in lower density by farmers with higher units of farm parcels indicates that fragmented farmlands are less convenient for practicing best practices compared to consolidated farmlands. This could be because of the higher follow-up and resource requirement of fragmented farmlands compared to continuous farmlands. This finding coincides with Hartvigsen (2014) argument that landholding divided into several parcels hampers agricultural development and requires land consolidation instruments.

The minimal effect of wealth status difference among households might be because practicing *R. prinoides* agroforestry requires less financial capital. The higher likelihood of practicing *R. prinoides* agroforestry by middle-income households indicates that *R. prinoides* planting is less capital-intensive. Although the significance of wealth status is not pronounced in this practice, many studies found a positive correlation between income and adoption of best practices (Franzel 1999; Deressa et al. 2009), which assumed that the implementation of agricultural technologies requires sufficient financial well-being of the community (Knowler and Bradshaw 2007).

5.5 Conclusion

Smallholder farmers have long been utilized *R. prinoides* agroforestry to optimize and stabilize production and income from their limited landholdings. The practice enhanced the sociocultural and ecological benefits from their farmland amidst a changing climate and market environment. The benefits are achieved by integrating different species with complementary resource requirements and production seasons. *R. prinoides-based* agroforestry allows sustainable intensification by minimizing inputs, maximizing resource utilization and conservation, diversifying products, and mitigating the risks associated with production and market fluctuations. *R. prinoides* agroforestry enables farmers to maximize their income from their farmland compared to annual mono-cropping. The income from the sale of *R. prinoides* trees/shrubs products complements the production system. The sale of leaves harvested from the trees/shrubs is the main source of cash income and enables practicing farmers to purchase household necessities and reinvest to improve their livelihood. The product has also a multiplier effect and provides a business commodity for non-practicing people. Planting *R. priniodes* trees/shrubs ensures farmland use rights, tree ownership, and the right to transfer or inherit to their children. *R. priniodes* agroforestry empowers women through their higher involvement in management and income administration than men. The practice is a source of family and community employment primarily for females during the off-farming season. This enables increased labor productivity and reduces labor slack and peak times. *R. prinoides* agroforestry is socially inclusive, gender-sensitive and creates opportunities that enhance social capital. However, higher labor requirements and market variability are prevailing challenges of the farming system. The extent and performance of *R. prinoides* agroforestry is affected by agroecological and socioeconomic factors. Gender, age, family size, land ownership, farm size, farm fertility, farm parcels, and farmers' wealth status were significant determinants of practicing *R. prinoides* agroforestry. Farmer-based research, concerted extension services, and development efforts are required to enhance productivity, market efficiency, sustainability, and scale-up of local farming practices that incorporate trees/shrubs with valuable products and services. Thus, scaling up similar practices could enhance the socioeconomic well-being of smallholder farmers.

Chapter 6 Role of *Rhamnus prinoides*-based Agroforestry Practices by Smallholders in Climate Change Adaptation in the Drylands

6.1 Introduction

Conventional agricultural practices in developing countries have been contributing to climate variability and change (IPCC 2007) while being highly affected by its impacts (IPCC 2014). Agricultural growth and opportunities for economic development and poverty eradication are likely to slow down because of future climate variability and change (Wagesho et al. 2013; Dazé 2014). Significant influence of climate variability and extreme events are observed and expected to increase in the future (Dazé 2014). This is expected to be severe in drylands, considered a marginal environment characterized by challenging agro-climatic conditions, degraded natural resources and shortage of moisture to support primary production (Sietz et al. 2011; Tewari et al. 2014). Ethiopia is highly exposed to climate variability and change impacts (Conway and Schipper 2011; Krishnamurthy et al. 2014) due to environmental, socio-demographic, and economic factors (Dercon 2004; Deressa et al. 2009).

In developing countries like Ethiopia, continuous exposure to climate variability and change problems has prompted local people to develop locally effective coping and adaptation strategies. Coping and adaptation strategies are mostly planned to change in the short and long term, respectively (Brooks et al. 2005; Gallopin 2006). Its knowledge of the events and/or ability to modify or reduce its characteristics or behavior can describe the coping and adaptive capacity of any society or system in the environment (Gallopin 2006). In the developing world, adaptations to climate variability and change rely on past experiences (Adger et al. 2003) and it is the process of adjusting to experienced or expected climate-related risks (Brooks et al. 2005). The effectiveness of the adaptation process and social acceptability can be performance indicators of an adaptation strategy (Adger et al. 2005; Smit and Wandel 2006). Tailor-made scenarios are more effective than top-down options for adaptation planning (Carlsen et al. 2012). Compared with more global technological interventions, local strategies are generally cost-effective, participatory, and sustainable for adaptation (Anik and Khan 2012). However, despite their importance, local and indigenous strategies are rarely included in the design and implementation of modern adaptation efforts (Nyong et al. 2007).

Modern farming systems based on highly specialized farms that rely on annual mono-cropping with high inputs are less resilient to climate variability impacts (Kim et al. 2012; Abson et al. 2013). The uncertain weather conditions and commodity markets are causing less resilient farm production and income (FAO 2009). Diversifying production systems is hypothesized as a local strategy to be resilient to climate variability impacts (Verchot et al. 2007; Abson et al. 2013). Particularly, agroforestry systems that include significant trees/shrubs can be resilient to climate variability impacts because of their ability to maintain or modify their environment (van Noordwijk et al. 2021) and buffer against production and income risks for smallholder farmers (Verchot et al. 2007; Leakey 2012; Dawson et al. 2013). However, baseline information on the performance of local or indigenous agroforestry practices in different localities in the adaptation of climate variability impacts has been lacking and has become a major focus in research and development (Verchot et al. 2007; Sinclair and Coe 2019). Thus, this study is intended to examine the coping and adaptation potential of locally practiced diversified production systems that include a significant number of trees with high value products to climate variability impacts in smallholder farming system.

Many works are underway in climate smart agricultural practices (CSAP) mainly on developing and scaling-up staple food crops adapting to existing climate variability and change in Ethiopia as one of the Climates Resilient Green Economy (CRGE) strategy (FDRE, 2011). However, the attempt to explore indigenous farming practices' adaptation potential to the impact of climate variability and change is limited. Consequently, there is shortage of information regarding locally practiced *Rhamnus prinoides*-based agroforestry adaptation potential to climate variability impacts. Planting *R. prinoides* trees/shrubs, belonging to the family Rhamnaceae (Orwa et al. 2009), on crop field for its leaf harvest is an age-old practice by smallholder farmers in the drylands of Tigray, Ethiopia. *R. prinoides* agroforestry system is an indigenous practice that could have its unique attributes with potential for coping and adaptation of climate variability impacts.

The propensity to adapt and the choice of adaptation strategies are highly context-specific and dependent on many factors including level of education, gender, age, soil fertility, landholding, and wealth status (Adger et al. 2009; Bryan et al. 2009). Therefore, understanding the perceptions of local communities regarding climate variability (Maddison 2006; Bryan et al. 2009), the determinants of farmers' choices (Lambrou and Nelson 2013; Ashraf et al. 2014) and evaluating local adaptation mechanisms and integrating them with scientific and technological strategies (Nyong et al. 2007; Kasali 2011) is required to design and promote socially acceptable and locally effective coping and adaptation strategies (Denton 2002; Lambrou and Nelson 2013). However, the potentials and limitations of *R. prinoides* agroforestry practices are not yet studied, accordingly. Specifically, there is no empirical information on the contribution of *R. prinoides* agroforestry practices by smallholders for coping with and adaptation to climate variability associated impacts, while it has been providing different products and services for the local communities in the study area.

Therefore, the main objective of this study was to investigate the contribution of *R. prinoides*-based agroforestry practices and determinants of smallholders' choices in coping with and adapting to climate variability in the drylands of Tigray. Specifically, this study aims to (1) analyze how local people do perceive climate variability, (2) identify the coping and adaptation strategies to climate variability impacts practiced by smallholder farmers, (3) examine the role of *R. prinoides* agroforestry practices for coping with and adapting to climate variability impacts, and (4) investigate determinants of smallholder farmers' choices of coping and adaptation strategies to climate variability in the drylands.

6.2 Methods

6.2.1 Data Collection

Primary data was collected through household survey (section 3.3). Respondents were asked questions on their understanding of climate change, coping and adaptation mechanisms and the role of *R. prinoides* agroforestry, local criteria used for evaluation and selection of coping and adaptation strategies. Each respondent was asked for an opinion on the importance of each of the coping and adaptation strategies. Coping and adaptation strategy that was mentioned by each respondent was recorded as an observation. Therefore, for every coping and adaptation strategy from each of the respondents were 191 frequency observations, each having values ranging from 1 (when mentioned by one respondent), and 191 (when mentioned by all the respondents).

Additional primary data was collected from field observation on the distribution, spatiotemporal arrangement, management system and farm condition of *R. prinoides-based* agroforestry. Key informant interview with two agroforestry experts from the districts, three extension agents and three local administrators from the villages was conducted to assess the importance of local practices and the contribution of *R. prinoides* agroforestry to the livelihood of the local community under climate variability and their role in the development of best practices.

6.2.2 Analysis Method

Descriptive statistics was used for the analysis of the perception of local people on climate variability and its impacts, and contributions of coping and adaptation strategies. To inspect inter-annual and intra-annual variability of rainfall and temperature of the study area, coefficient of variation (CV) (NMSA 1999), precipitation concentration index (PCI) (De-Luis et al. 2000) and standardized rainfall anomaly (SRA) (Agnew and Chappel 1999) were applied. To detect the trend of rainfall and temperature of the study area based on 30 years (1977 to 2017) data from NMSA, linear regression was employed. A comparison of mean ranks of mono-cropping and *R. prinoides* agroforestry resilience to climate variability was done using the Kruskal-Wallis test. Factors influencing the number and choices of farmers' coping and adaptation measures were examined using Poisson and binomial regression models, respectively (section 3.3).

6.3 Result and Discussion

6.3.1 Local People's Perception of the Prevalence and Impacts of Climate Variability

Most of the respondents (90%) indicated that they believe there is climate variability. The perception comes from own experience (64.9%), meetings or training (15.7%) and media outlets (13.3%). Some of the climate variability stress variables that were mentioned by most respondents include shortage of rainfall (73%), late begin and early cessation of rainfall (60%), outbreak of pest and diseases (56%), hail (50%), flooding (23%) and drought (13%). Farmers pointed out that uncertain rainfall patterns are affecting their farming systems and subsequently forcing them to adjust. A larger share of farmers that are aware of climate variability could be important for adapting to climate impacts through better practices (Bryan et al. 2009). In most cases, farmers' perception of climate variability using indicators mainly from their farming activities perspective was found to be in line with climate data (Figure 6.1). Most of the farmers correlate climate variability with deforestation and natural resource degradation, while few relate it with the punishment of God for bad actions. According to the farmer's view, while the severity varied, climate variability stresses have been leading to a shortage of moisture (water), and consequently reduced crop and forage yield, and total crop failure. Likewise, Alemayehu and Bewket (2016) reported that smallholder farmers from central Ethiopia are facing different types of climate variability-related risks, such as reduced or variable rainfall, warming temperatures, and increased occurrence of crop and livestock pests and diseases, flooding, shortage of water and soil erosion.

According to the perception of the respondents, climate variability has large negative impacts on the social, economic, and environmental aspects of the community. Some of the climate variability-caused problems that were mentioned by most respondents include shortage of food (84%), shortage of domestic water (73%), shortage of livestock feed (72%) and shortage of cash (52%). This is in line with Wagesho et al. (2013)'s argument that climate variability will reduce agricultural production and aggravate poverty. Though the impact of climate variability largely depends on how farms are managed, it has significant influences on agricultural production and productivity (Bryan et al. 2013). Planting of *R. prinoides* trees on crop fields in rain-fed farming systems is found to buffer the impacts of climate variability for practicing farmers (70%) in the study area.

6.3.2 Climate Trend and Variability

The annual rainfall of the study area showed moderate inter-annual variability with a CV of 26.7%. The main rainy season (summer) from June to September, the second rainy season (spring) from March to May, and the dry season (winter) from October to February rainfall showed high variability with CV of 37.8%, 52.4%, and 80.8%, respectively. The monthly rainfall of June, July and August showed high variability with the CV of 94.12%, 47.08%, and 54.04%, respectively, while it is the main cropping time in the study area. The annual rainfall shows moderate concentration in a few months of the year with a PCI value of 16.1 according to De-Luis et al. (2000) classification, having 49.5% of the annual rainfall in July and August. The annual and summer rainfall showed increasing while spring and winter showed declining but with non-significant trend (Figure 6.1a). The driest years in the study area were 1978, 1983, 1988, 1999, and 2013 with SRA values between -1.28 and -1.65, while 1981, 1993, 1994, 1996, 1997, and 2006 were the wettest years, according to Agnew and Chappel (1999) classification. The mean temperature showed less inter-annual and intra-annual variability with a CV of 7.6%, 8.0%, 8.4%, and 7.9% for annual, summer, spring, and winter, respectively. The annual, summer, spring, and winter mean temperatures showed a significant increasing trend since 1977 (Figure 6.1b).

From the smallholder farmers' point of view and climate data analysis, the most worrisome component of climate variability is increased inter-annual and monthly variability in rainfall pattern. Rainfall in the Tigray regional state is highly variable in both annual and seasonal totals (Figure 6.1a). Shortage of rainfall and erratic nature of rainfall has been constraint of production in the regional state. Generally, changes in rainfall patterns which cause both droughts and floods are mostly mentioned as the cause for the poor performance of agriculture in Ethiopia (Deressa et al. 2009; Conway and Schipper 2011). The types of coping and adaptation strategies used by farmers are important to reduce the impact of current climate variability on agricultural production and ensure the future sustainability of agriculture in Ethiopia (Alemayehu and Bewket 2016).

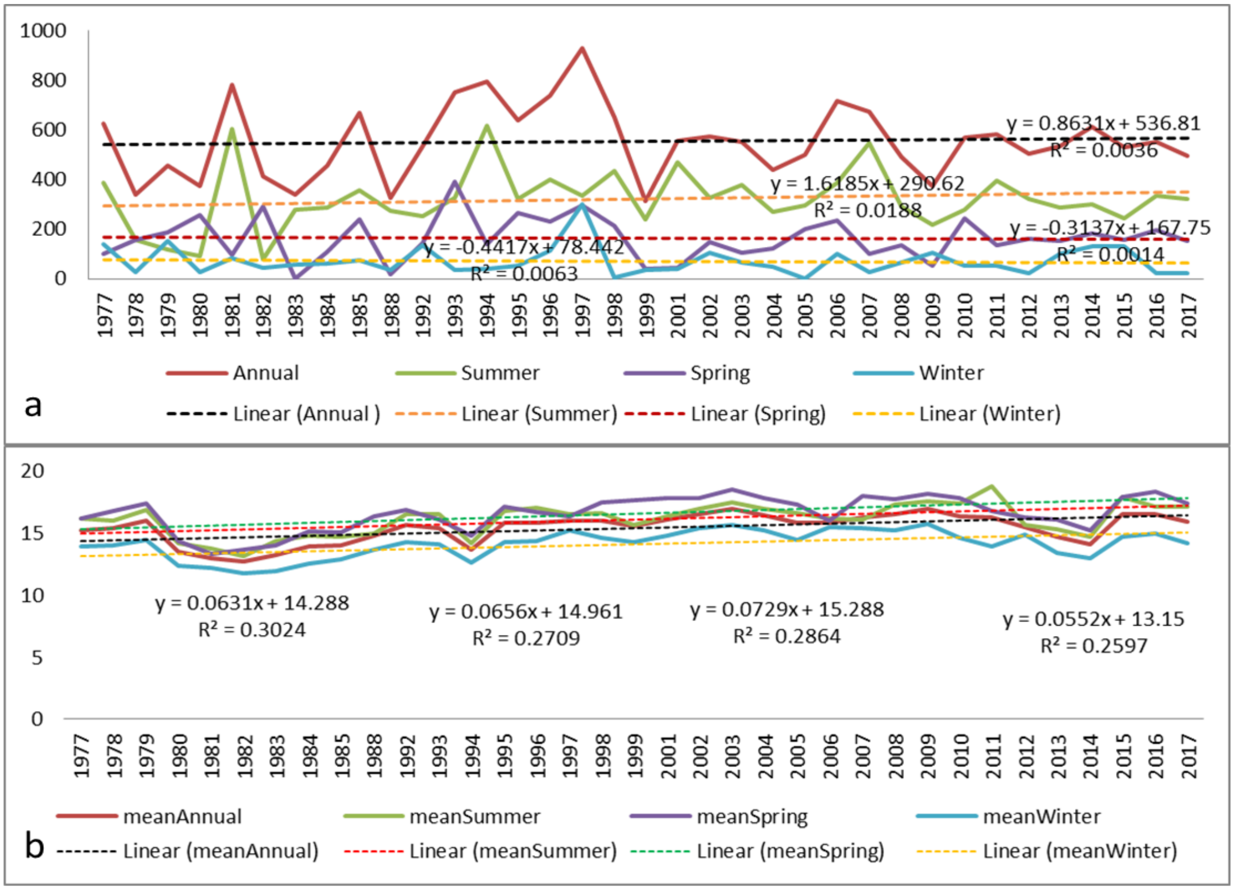

Figure 6. 1 Trend and variability of annual and seasonal rainfall (mm) (a) and mean annual and mean seasonal temperature (^{O}C) (b) of the study area from 1977 to 2017.

6.3.2 Coping and Adaptation Strategies to Climate Variability Impacts by Smallholders

Most of the coping-up measures for climate variability impacts taken by smallholder farmers in the study sites (Table 6.1) are similar to what Deressa et al. (2009) reported from other parts of

Ethiopia except for *R. prinoides* leaves sale. Most of the respondents who practice *R. prinoides* agroforestry rely mainly on *R. prinoides* leaves sale to cope-up climate variability impacts. Most of the adaptation strategies practiced by smallholder farmers in the study sites (Table 6.1) were found enlisted by Ethiopia's National Adaptation Program of Action (NAPA 2007) except *R. prinoides-based* agroforestry practice. The most widely practiced adaptation strategies for climate impacts were those with relatively less cost to the household and relatively easy to implement. In this study, we observed that most of the adaptation strategies are complementary to each other. For instance, soil and water conservation is important to improve soil moisture which is important to increase the harvest from *R. prinoides* agroforestry and the income from *R. prinoides* leaves sale is important to purchase improved seeds.

R. prinoides-based agroforestry is extensively practiced (70.2%) mixed cropping in the study area. Mixed cropping or intercropping is an adaptation strategy practiced by the local people through diversifying crop types on farmland. Mixed cropping is the growing of two or more crops (annual and/or perennial) simultaneously on the same piece of farmland that enhances intensification in time and space to enhance yield. This is important to compensate for production failure and diversify products at the same time or year from the same land area. Besides, most of the farmers (61.3%) cultivate annual crops in rotation with and without *R. prinoides* to enhance soil fertility, reduce pest and disease outbreaks, and improve production. Moreover, most of the farmers (57.1%) used improved crop variety to cultivate with and without *R. prinoides* for better productivity under climate impacts. In addition to this, most of the farmers (52.4%) used to switch sowing time and crop type to adapt to the early or late start and early cessation of rainfall. Most of the coping and adaptation strategies practiced by farmers were found to be complementary to each other in resource requirement, practicing season, and production. This complementarity enables farmers to improve their productivity and coping and adapting capacity to seasonality and climate impacts. Likewise, Lasco et al. (2011) indicated that introducing diverse farming systems and technologies helps smallholder farmers to be resilient to the impact of climate stress.

Table 6. 1 Smallholder farmers coping and adaptation measures (N=191)

Coping measures	Total (%)	Adaptation measures	Total (%)
Reduced food consumption	55.5	*R. prinoides* agroforestry	70.2
Livestock sale	62.8	Using improved variety (seed)	57.1

Using tree fodder	47.1	Switching sowing time and crop type	52.4
Purchase food	23.6	Crop rotation	61.3
Purchasing forage	23.6	Soil and water conservation	78
Fetching water from far	76.4	Planting fodder trees	47.6
Reduced water consumption	34.6	Water harvesting	8.9
Borrowing	51.3		
R. prinoides leaves sale	57.3		
Labor sale (casual labor)	33		
Aid and safety-net	33.5		

6.3.3 Role of *R. prinoides-based* agroforestry practice to the adaptation of climate variability

R. prinoides-based agroforestry practice is found to be resistant to climate variability impacts because of its seasonal and perennial components compared to annual crops in mono-cropping practices (Table 6.2). Specifically, farmers observed that annual crops intercropped with *R. prinoides* were resistant to climate variability compared to the same type of crops mono-cropped in similarly managed farmlands because of the amelioration effect of *R. prinoides* trees. Farmers' observation coincides with Gebremeskel et al. (2017) report of better moisture in farmlands with *R. prinoides* trees compared to nearby farmlands without trees. Tobella et al. (2017) and Gao et al. (2018) reported spatially, and temporally complementary water use between trees and annual crops in semiarid agroforestry systems during dry or drought conditions that improved yield. Moreover, many study reported that trees in agroforestry farms can enhance the associated crop growth as trees can buffer climatic extremes that affect crop growth and improve microclimate by reducing incident solar radiation and reducing air and soil temperature while improving water status, gas exchange and water use efficiency (Lott et al. 2009; Mbow et al. 2014; Tewari et al. 2014; Sida et al. 2018).

Most farmers realized that *R. prinoides* agroforestry is an effective strategy to adapt to rainfall distribution problems. This is because *R. prinoides* as a perennial plant can make use of rainfall that comes throughout the year and available moisture which could increase *R. prinoides* annual leaves harvest and achieve relatively stable annual production compared to annual crops in a mono-cropping system. This coincides with Lott et al. (2009) report on the ability of trees on farmland to utilize off-season rainfall and residual soil water after the cropping period during the dry season. Likewise, some studies reported that agroforestry systems contribute to climate change adaptation through shift in resource capture to adjust to changing conditions (van Noordwijk et al. 2021) and enable farmers to better manage weather-related shocks (Krishnamurthy et al. 2019; van Noordwijk et al. 2021). Moreover, Tewari et al. (2014) reported that farming systems that incorporate trees/shrubs provide greater resiliency to inter and intra-annual variability through increased resource-use efficiency and crop diversification produced seasonally.

Most of the *R. prinoides* trees on farmland under our investigation (Figure 6.2) were 15 to 40 years old and have been resilient to the climate variability problems in the last two to four decades. Besides, farmers reported that farmlands with *R. prinoides* plantations have been providing varied annual production under climate variability while the annual crops in the mono-cropping system have faced the risk of total failures of annual production (Table 6.2). Similarly, Jose et al. (2009) and van Noordwijk et al. (2021) stated that trees can maintain production during wetter and drier years because woody perennials make gains through their root and canopy architectures for the accumulation of growth resources. Tobella et al. (2017) and Gao et al. (2018) reported that agroforestry systems in semiarid demonstrate resilience to climate variability impacts because of the facilitative interspecific water interactions during dry or drought conditions among perennial and annual crops. Moreover, some studies reported that agroforestry practices well-buffered climate variability impacts and reduce moisture stress during low rainfall years because of permanent tree cover, varied ecological niches and diverse functions (Smit and Wandel 2006; van Noordwijk et al. 2021) that enable increased soil porosity, reduced runoff and increased soil cover that led to increased water infiltration in the soil profile (Jose et al. 2009; Tewari et al. 2014).

Table 6. 2 Farmers' ranking scores (1 for the lowest and 5 for the highest) on the resistance of cropping types to the impact of climate variability

Cropping type	Resistance mean rank difference to climate variability variables						
	Late beginning and early out rain	Shortage of rain	Drought	Hail	Flood	Pest	Diseases
Monocrops	2.25^{a}	2.23^{a}	1.98^{a}	1.92^{a}	2.04^{a}	3.26^{a}	2.64^{a}
Crop with *R. prinoides*	2.88^{b}	3.07^{b}	2.75^{b}	2.97^{b}	3.22^{b}	2.25^{b}	2.61^{a}
R. prinoides	4.72^{c}	4.48^{c}	4.01^{c}	4.22^{c}	4.60^{c}	4.48^{c}	4.68^{b}

Kruskal-Wallis test at 0.05 significance level and crop types with different superscripts along the column are significantly different.

Farmers indicated that the condition of farms with *R. prinoides* is better than farms with annual crops mono-cropping. Farmers' view coincides with our field observation and Gebermeskel et al. (2017) report that found better organic matter and moisture content, and minimal erosion indicator s on farms with *R. prinoides* plantation compared to nearby open farms. This coincides with Tewari et al. (2014) and Krishnamurthy et al. (2019) report that agroforestry systems in the drylands of India and Latin America improve soil fertility and water use efficiency. van Noordwijk et al. (2021) also stated that agroforestry enhances adaptation to climate impacts through improving microclimate and reversing negative trends. Likewise, Sida et al. (2018) reported increased soil fertility, improved water use efficiency, reduced heat stress, and increased crop yield from *Faidherbia albida* based agroforestry in the central rift valley of Ethiopia.

R. prinoides-based agroforestry was found to be a means for sustainable intensification of farm production for smallholding farmers in the study area (Table 6.3). Most farmers and Gebremeskel et al. (2021) reported that the annual production of farms with *R. prinoides* plantations have been more than doubled compared to farms with annual crops mono-cropping, keeping farm conditions and management inputs similar. Similarly, Tewari et al. (2014) and Krishnamurthy et al. (2019) reported that agroforestry in the drylands of India and Latin America with higher yield and income than mono-cropping. Farmers reported that *R. prinoides-based* agroforestry requires fertilizer input at a similar scale with annual crops mono-cropping, while it produces higher than mono-cropping. Moreover, most of the farmers used improved variety crops (57.1%) and cultivated crop types in rotation (61.3%) in farmlands with *R. prinoides* plantation to improve productivity. *R. prinoides* agroforestry was intensifying production through efficient utilization of farm and labor resources throughout the year, diversified products and production season, commercializing subsistence farming, resilience to climate (rainfall) variability, and improving farm conditions (Table 6.3). Gockowski and Asten (2012) and Garnett et al. (2013) indicated the importance of integrating trees in land use systems for sustainable intensification of agricultural production. Likewise, Jose et al. (2009) observed that tree-based systems have comparative advantages to exploring a larger soil volume for water and nutrients through their deep root system and maintaining production during wetter and drier years. Accordingly, agroforestry has been suggested as an alternative solution to increase farmland and labor resource utilization efficiency, reducing environmental degradation, and buffering against production and income risks for farmers (Paul et al. 2017).

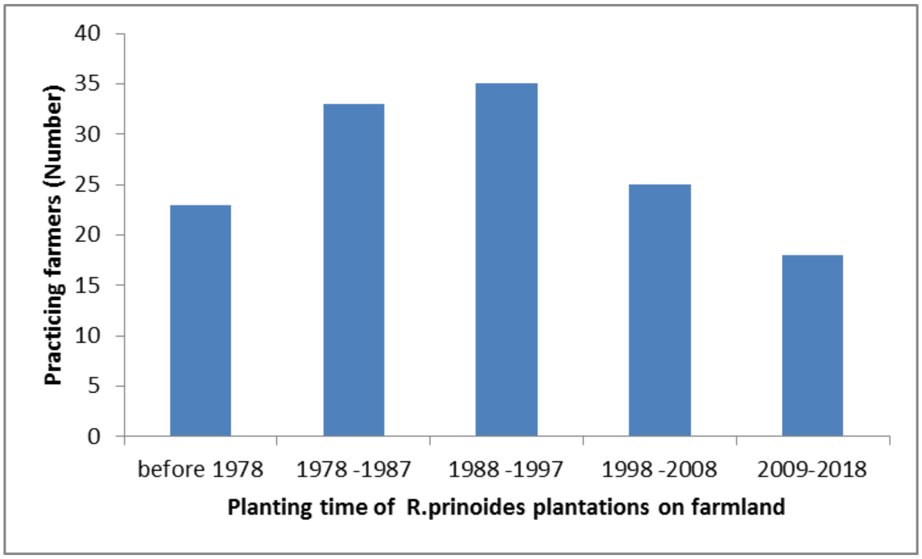

Figure 6. 2 The duration (age) of *R. prinoides* plantations on farmland of the practicing farmers

Most farmers reported that *R. prinoides-based* agroforestry is a means to diversify farm products and production season that enables smallholding farmers to buffer production and income risks of climate variability in the study area (Table 6.3). This coincides with Verchot et al. (2007) and Sanchez (2000) argument that the objective of smallholder farmers' practicing agroforestry system could go beyond increasing net production that includes diversifying products and maintaining stability of production to adapt production and income variability caused by climate variability. The main products of *R. prinoides* agroforestry include staple crops harvested from the rainy season and *R. prinoides* leaves harvested mainly in the dry season and slightly in the rainy season. Farmers partially harvest ripened *R. prinoides* leaves three times a year and the harvesting periods are first in January, second in May, and third in September, from 4 years up to 50 years old trees (Gebremeskel et al. 2021). Properly dried *R. prinoides* leaves can be stored in a clean and dry warehouse for more than a year which enables farmers to wait for better price sales. *R. prinoides* leaves sale from each harvest helps subsistence farmers generate cash income that enables them to reduce income shortfalls after the main harvest. Thus, agroforestry systems could enable the creation of more diversified enterprises with greater income distribution over time that can provide greater economic stability and reduced risk under climate variability change (Cubbage et al. 2012).

R. prinoides was observed to be vigorous and greener in the dry season while it terminates its apical dominance and shades its leaves in the rainy season in the study area. The inverse phenology (hydro-dormancy) of *R. prinoides* could facilitate its complementarity, reduce competition with associated annual crops in resource use, and reduces its shading effect on the understory crops. Similarly, Muthuri et al. (2009) and Sida et al. (2018) observed that differences in leaf phenology among agroforestry trees and crops improved water use efficiency, gaseous exchange, tree growth, and productivity of accompanying crops. Gill (1991) demonstrated that trees formed the basis of counter-seasonal strategies because of intercrop differences in growing and production period and season, tolerance of adverse climatic conditions, level of inputs, and cultivation requirements. Likewise, some studies reported that diversified production systems that include trees/shrubs resistant to seasonal variation and drought can provide products year-round (Feyssa et al. 2011), spread income and resource requirements throughout the year because different species produce at varied time and way (Isbell et al. 2011).

Farmers reported that *R. prinoides* agroforestry's trees/shrubs product is mainly for sale while the annual crops product is mainly for consumption (Table 6.3). Most of the respondents (70.2%) reported that their main source of cash income is from *R. prinoides* leaves sale. Some of the respondents (57.3%) rely on the income from *R. prinoides* leaves sale for the purchase of food at the times of crop failure and critical times of food shortage before the main harvest. *R. prinoides-based* agroforestry has a multiplier effect in the community being an important source of income for subsistence farmers, a source of employment, and being business commodity for retailers, exporters, and local beer brewers (Gebremeskel et al. 2021). Likewise, some studies reported that diversified production systems that include a significant tree/shrub component with higher values could provide both staples and marketable tree products to improve livelihoods (Leakey 2012; Dawson et al. 2013) and may buffer against production and income risks associated with climatic variability (Verchot et al. 2007). Feyssa et al. (2011) reported that farmers in the semiarid central Ethiopia prefer trees that provide food, forage, and income in the dry season and critical times. Similarly, Gill (1991) reported that the income from sales of cash tree products that were used mainly to buy basic food and medicines before the main harvest accounts for a significant share of poor farmers' total income.

Table 6. 3 The role of *Rhamnus prinoides*-based agroforestry in the adaptation to climate variability impacts for the practicing smallholders.

Impacts of climate variability	Role of the agroforestry systems to the adaptation of climate variability impacts		
	Role played	Response (%)	Justifications given
Production reduction	Maximize farm production	98.1	Integration of trees/shrubs intensifies farm production through efficient farm and labor resources utilization throughout a year for years (30 years on average)
	Stabilize annual production	63	Integration of trees/shrubs reduces production failure in years with variable and/or shortage of rainfall because of their better resilience
Income reduction	Maximize farm income	100	The sale of trees/shrub products with better market value enables to maximization of farm income
	Stabilize annual income	83	Diversified production time and farm products (commercial leaves and staple crops) reduce loss of income under market and climate variability
	Multiplier effect		Source of income for local daily laborers and traders
Soil fertility depletion and/or degradation	Improve soil fertility	37	*R. prinoides* trees/shrubs improve soil condition through leaves shade and litter fall, less wind and water erosion and reduced nutrient leakage because of continuous cover and access to deeper soil horizons
Aggravating microclimate stress mainly in the drylands	Amelioration of microclimate	37	*R. prinoides* trees/shrubs reduce climate extremes through reducing incident solar radiation, reducing air and soil temperature, improving soil moisture status and moisture use efficiency because of continuous cover
Prolonging seasonality problems	Bridging seasonal gaps	75	The varied cultivation and production time of trees and annual crops enable to utilization of farm and labor resources and provide products at varied times in a year, Storable products of the practice enable one to wait for better prices, Inverse phenology (hydro-dormancy) of *R. prinoides* reduces competition and shading effect on associated annual crops
Complicating sociocultural problems	Enhance sociocultural services	54	Source of employment to community members (mainly women) and assures land use rights, Means of social cohesion and networking through labor exchange, product sharing and exchange in-kind and business interactions Maintain community in their locality with their sociocultural values (reduce migration and conflict) because of improved and sustainable productivity

Above all, most of the respondents (87%) indicated that the number of farmers practicing *R. prinoides*-based agroforestry and the share of the practice from the landholding of each household has been increased through time since 1974. *R. prinoides* plantation on cropland covered 58.9%

of the practicing farmers' landholding on average. This might indicate that farmers have been expanding *R. prinoides* agroforestry learning from their own and neighbors' experiences on the importance of *R. prinoides* planting for coping with and adapting to climate variability and change impacts through time. Likewise, Adger et al. (2003) and Brooks et al. (2005) reported that in the developing world experience and the process of adjusting to experienced or expected change determines adaptations to climate variability and change. Kmoch et al. (2018) reported that co-learning and cooperation among farmers could replicate and scale up positive experiences and training in climate change adaptation. Besides, Anik and Khan (2012) stated that coping and adaptation strategies that are based on local or indigenous practices are relatively adaptive, cost-effective, participatory, and sustainable.

6.3.4 Determinants of coping and adaptation strategies for climate variability impacts

Gender, age, and education of household head, family size, land ownership, farm size, farm fertility, farm parcels, wealth status, and climate awareness were the determinants of the number and choices of coping and adaptation practices (Table 6.4 and 6.5). Male-headed are expected to use more tree fodder to supply the shortage of forage, to sale 2.12 times more labor to subsidize the shortage of income, practice 2.65 times more *R. prinoides* agroforestry and 2.33 times more fodder tree planting while 0.36 times less crop rotation than female-head households. The lower likelihood of practicing crop rotation to improve farm fertility and productivity by male-headed might be due to their lower seed management know-how or higher income to purchase chemical fertilizers compared to female-headed households. The overall higher choices of coping and adaptation practices by male-headed households might be because of the sociocultural and environmental factors that enable males to have more options than females. Similarly, Denton (2002) concluded that male-headed are more likely to embrace more alternatives and take risky businesses than female-headed households because of their access to information about new technologies and existing environmental conditions.

Table 6. 4 Poisson regression of determinants of the number of coping and adaptation measures adopted by smallholders

Factors	Coping strategies		Adaptation strategies	
	Coefficient	SE	Coefficient	SE
Gender (1 if male)	0.09	0.08	-0.02	0.09
Age (years)	0.01	0.01	0.002	0.01
Education (years)	0.01	0.01	0.03*	0.011
Family size (count)	0.07***	0.02	0.07***	0.02
Land ownership (1 if parent)	-0.05	0.12	-0.22*	0.15
Farm size (ha)	0.60**	0.28	0.94***	0.31
Farm fertility (1 if medium)	-0.05	0.07	-0.03	0.08
Farm fertility (2 if shallow)	-0.11	0.13	-0.30*	0.16
Farm parcels (count)	-0.16***	0.05	-0.20***	0.06
Wealth status (1 if medium)	-0.05	0.14	-0.02	0.16
Wealth status (2 if low income)	-0.06	0.15	-0.09	0.17
Climate awareness (1 if yes)	0.25*	0.13	0.09	0.14
Model fitness (R^2)	0.33		0.37	

*Significant at 0.1 level, **significant at 0.05 level, ***significant at 0.01 level in Poisson regression

Household heads older than a year are expected to practice more livestock sales and *R. prinoides* agroforestry. This might be result of the comparative advantages of elder farmers in farming experiences. Likewise, studies in Ethiopia have shown a positive relationship between number of years of experience in agricultural activities and the implementation of improved agricultural technologies (Maddison 2006; Deressa et al. 2009). Household heads with better education by a unit level are expected to adopt more adaptation strategies. Besides, household heads with better education at a unit level are likely to practice more food and forage purchase, *R. prinoides* leaves and labor sale, improved variety, shifting crop types, and sowing time, while 0.36 times less borrowing. Likewise, Maddison (2006) and Sood and Mitchell (2009) reported a positive relationship between the education level of household heads and adaptation to climate variability. Farmers with higher levels of education adapt better to climate variability (Deressa et al. 2009) because it is believed to be associated with access to information on improved technologies, ready to adapt new ideas, enable farmers to make innovative decisions and higher productivity, realize the diversification or specialization of livelihood activities and technology as coping and adaptation strategies (Ndambiri et al. 2013). The opposite relationship of education with borrowing might indicate the risk averseness of people with better education.

Households with larger units of family size are likely to practice more coping and adaptation mechanisms. Besides, households with larger units of the family are more likely to practice reducing consumption, purchasing food and forage, using tree fodder, *R. prinoides* leaves and labor sale, improved varieties, switching sowing time and crop types, crop rotation, soil and water conservation and planting fodder trees. Similarly, Croppenstedt et al. (2003) and Deressa et al. (2009) stated that households with larger family size are more likely to adapt to climate variability than the smaller family size because of their larger pool of labor that can be used to implement various agricultural technologies and in on-farm and off-farm activities.

Farmers who rely on their parents' farmland are likely to practice less coping and adaptation strategies compared to farmers who own farmlands. Besides, farmers relying on parents' farmland are likely to practice less purchase forage, *R. prinoides* leaves sale, *R. prinoides* agroforestry, improved varieties, switching sowing time and crop type, while 3.75 times more consumption reduction and 3.12 more labor sale compared to farmers who own farmland. This indicates that landless people have limited choices compared to landowners for the adaptation of climate impacts. Likewise, studies from Africa reported that farmers with a sense of tenure security were more likely to adapt better to climate change (Gbetibouo et al. 2010; Fosu-Mensah et al. 2012). Households with larger units of farms are likely to practice 1.82 times more coping and 2.56 more adapting strategies. Besides, households with larger units of farms are likely to practice 29.53 times more *R. prinoides* leaves sales, 20.70 more food and 33.48 more forage purchase, 73.63 more *R. prinoides* agroforestry practice, 49.12 more using improved variety, 61.34 more shifting crop type and sowing time and 1.38 times more crop rotation. This indicated that despite the overall small landholding in the study area, slight differences could affect farmers' coping and adaptation strategies for climate variability impacts. In line with this, Deressa et al. (2009) and Sood and Mitchell (2009) indicated that a larger farm size is expected to increase the coping and adaptation strategies to climate variability impacts in Ethiopia because it is highly associated with greater wealth.

Farmers with fragmented holding are likely to practice less coping and adaptation measures. Farmers with higher units of farm parcels are less likely to practice food and forage purchases, *R. prinoides* leaves sale, *R. prinoides* agroforestry, improved varieties, switching sowing time and crop type and crop rotation. This indicates that consolidated farmlands are convenient for introducing adaptation strategies compared to fragmented farmlands. Farmers having farmlands with poor fertility are likely to adopt fewer adaptation measures compared to farmers with fertile farmlands. Farmers having farmlands with poorer fertility are likely to practice less livestock and *R. prinoides* leaves sale, *R. prinoides* agroforestry, switching sowing time and crop type, while 4.10 times more borrowing compared to farmers having fertile farmlands. This might indicate that farmers with fertile farms have more livestock and *R. prinoides* for sale, while farmers with poor fertility rely on borrowing to get cash income at critical times. Likewise, studies from Asia and Africa reported that soil fertility has a positive relation to the use of climate variability adaptation measures (Sood and Mitchell 2009; Fosu-Mensah et al. 2012).

Households with medium and low wealth status are likely to practice less *R. prinoides* leaves sale, and improved varieties, while 7.24 and 1.32 times more *R. prinoides* agroforestry, respectively, compared to higher income households. This might indicate that poor farmers are constrained to use improved variety because of its cost, while they are practicing more *R. prinoides* agroforestry to improve their income. Although the significance of wealth status is not pronounced in this study, many studies found a positive correlation between income and adaptive capacity (Deressa et al. 2009) because the implementation of new agricultural technologies assumed that requires sufficient financial well-being of the community (Knowler and Bradshaw 2007). Farmers with better climate awareness are likely to practice more coping measures. Besides, household heads with better climate awareness are expected to practice 2.75 times more livestock sales, 9.45 more R. *prinoides* leaves sales and 3.87 times more improved varieties. Likewise, Maddison (2006) reported that to improve people's readiness to adopt new ideas and realize the diversification or specialization of livelihood activities and technology as adaptation strategies to the impact of climate variability requires better climate awareness.

Table 6. 5 Binary logistic regressions of determinants of choice of coping and adaptation measures adopted by households

Factors	Coping and adaptation strategies						
	Reducing consumption	Purchasing food	Livestock sale	Using tree fodder	Purchasing forage	*R. prinoides* leaves sale	Borrowing
Gender (1 if male)	*ns*	*Ns*	*ns*	0.91(0.36)**	*Ns*	*ns*	*ns*
Age (years)	*ns*	*Ns*	0.03(0.02)*	*Ns*	*Ns*	*ns*	*ns*
Education (years)	*ns*	0.15(0.06)**	*ns*	*Ns*	0.21(0.07)***	0.18(0.08)*	-0.24(0.06)***
Family size (count)	0.28(0.09)***	0.20(0.10)**	*ns*	0.22(0.89)**	0.24(0.11)*	0.24(0.13)**	*ns*
Land ownership (1 if parent)	1.32(0.52)**	*Ns*	*ns*	*Ns*	-1.42(0.82)	-2.51(1.15)**	*ns*
Farm size (ha)	*ns*	3.03(1.31)**	*ns*	*Ns*	3.51(1.51)**	5.69(1.71)***	*ns*
Farm fertility (1 if medium)	*ns*	*Ns*	-0.91(0.37)**	*Ns*	*Ns*	-0.63(0.41)	-0.71(0.34)**
Farm fertility (2 if shallow)	*ns*	*Ns*	-0.33(0.58)	*Ns*	*Ns*	-2.58(1.51)**	1.41(0.68)**
Farm parcels (count)	*ns*	-0.51(0.24)**	*ns*	*Ns*	-0.54(0.29)*	-0.80(0.33)**	*ns*
Wealth status (1 if medium)	*ns*	*Ns*	*ns*	*Ns*	*Ns*	-1.36(0.85)	0.09(0.70)
Wealth status (2 if low income)	*ns*	*Ns*	*ns*	*Ns*	*Ns*	-1.75(0.90)*	1.00(0.74)
Climate awareness (1 if yes)	*ns*	*Ns*	1.01(0.51)**	*Ns*	*Ns*	2.25(1.17)*	*Ns*
Model fitness R^2	0.06	0.08	0.07	0.05	0.11	0.10	0.12
AIC	254.54	242.27	249.34	258.73	198.05	230.42	245.31
	Labor sale	*R. prinoides* agroforestry	Improved variety	Switching STCT	Crop rotation	Soil & water conservation	Planting fodder trees
Gender (1 if male)	0.75(0.43)*	0.98(0.54)*	*ns*	*Ns*	-1.03(0.43)**	*ns*	0.85(0.36)**
Age (years)	*ns*	0.09(0.03)***	*ns*	*Ns*	*Ns*	*ns*	*Ns*
Education (years)	0.16(0.06)***	*Ns*	0.17(0.07)**	0.21(0.07)***	0.29(0.07)***	ns	*Ns*
Family size (count)	0.24(0.10)**	*Ns*	0.27(0.11)**	0.16(0.10)*	0.32(0.11)***	0.38(0.11)***	0.25(0.09)***
Land ownership (1 if parent)	1.14(0.51)**	-2.06(0.78)***	-1.61(0.59)***	-1.33(0.58)**	*Ns*	*ns*	*Ns*
Farm size (ha)	*ns*	6.60(2.23)***	3.89(1.41)***	4.12(1.37)***	3.09(1.36)**	*ns*	*Ns*
Farm fertility (1 if medium)	*ns*	-0.72(0.52)	*ns*	-0.49((0.35)	*Ns*	*ns*	*Ns*
Farm fertility (2 if shallow)	*ns*	-3.18(0.84)***	*ns*	-1.26(0.62)**	*Ns*	*ns*	*Ns*
Farm parcels (count)	*ns*	-1.33(0.39)***	-0.93(0.28)***	-0.96(0.27)***	-0.47(0.26)*	*ns*	*Ns*
Wealth status (1if medium)	*ns*	1.98(1.02)*	-2.15(1.19)*	*Ns*	-0.91(0.84)	*ns*	*Ns*
Wealth status (2 if low income)	*ns*	0.28(1.01)	-2.60(1.20)**	*Ns*	0.05(0.87)	*ns*	*Ns*
Climate awareness (1 if yes)	*ns*	*Ns*	1.35(0.62)**	*Ns*	*ns*	*ns*	*Ns*
Model fitness R^2	0.25	0.46	0.21	0.14	0.17	0.07	0.05
AIC	191.87	147.05	225.58	243.07	229.13	192.06	257.61

Overall, the number of observations was 191, *Significant at 0.1 level, **significant at 0.05 level, ***significant at 0.01 level while *ns* is the non-significant variable removed by backward method, VIF is variance inflation factor, dwt is Durbin Watson test, AIC is Akaike information criterion, multicollinearity test (VIF < 2), independence test (1< dwt < 2), linearity test (interaction terms not significant at 0.05 level).

6.3.5 Conclusion

R. prinoides-based agroforestry is an indigenous climate-resilient farming system that is widely practiced in the study area. Climate variability problems that are mainly expressed with rainfall uncertainties are prevalent in the study area. Indigenous farming systems have been playing a significant role in coping with and adaptation to climate variability impacts for the smallholder farmers. *R. prinoides-based* agroforestry is a means to cope-up and adapt to climate variability impacts through component and product diversification with complementary resource requirement and production season, sustainable farm yield intensification, and stabilization of annual farm production. Besides, the cash income from *R. prinoides-based* agroforestry is the source of savings for farmers to be invested in different coping and adaptation measures. In addition to this, *R. prinoides-based* agroforestry found to be complementary with other adaptation strategies that include soil and water conservation, use of improved varieties, crop rotation, switching crop type, and sowing time. *R. prinoides-based* agroforestry is socioeconomically and agro-ecologically appropriate indigenous coping and adaptation strategies for smallholder farmers in drylands. Smallholder farmers' choice of coping and adaptation strategies is found to be influenced by socioeconomic and biophysical factors that require to be well understood to design and implement locally acceptable and effective adaptation strategies. Hence, indigenous farming systems that incorporate trees/shrubs such as *R. prinoides-based* agroforestry that enhance the coping and adaptation capacity of smallholding farmers need to be explored, appreciated, improved, scaled up, and sustained.

Chapter 7 Role of *Rhamnus prinoides*-based Agroforestry Practice in Climate Change Mitigation[2]

7.1 Introduction

Agroforestry plays a significant role in both climate change mitigation and adaptation to climate change impacts (Garrity 2004; Morgan et al. 2010; Schoeneberger 2005). Agroforestry carbon sequestration potential can be increased up to 90-150 Mg C ha^{-1} year^{-1} over a potential area of 900 million ha (Garrity 2004; Leakey 2010). Agroforestry systems have 50 - 75 Mg C ha^{-1}year^{-1} higher than traditional treeless agricultural systems (Matocha et al. 2012). Agroforestry systems' carbon stocks may range from 29-228 Mg C ha^{-1}year^{-1} (Matocha et al. 2012; Mbowet et al. 2014). Global estimates for the C sequestration potential of agroforestry systems over 50 years range between 1.1 and 2.2 Pg C year^{-1} (Dixon 1995). Compared to monocultures, agroforestry systems are more efficient in capturing the resources available at the site for biomass growth and result in higher C inputs to the soil (Nair et al. 2010). Higher soil organic carbon (SOC) pools in agroforestry systems can be achieved by increasing the amount of biomass C returned to the soil (Cardinael et al. 2018) and by strengthening soil organic matter (SOM) stabilization or by decreasing the rate of biomass decomposition (Sollins et al. 2007; Rasse et al. 2005). Agroforestry systems store more C in deeper soil layers near trees than away from trees (Nair et al. 2010; Kell 2012).

The effectiveness of agroforestry practice in storing carbon depends on both environmental and socioeconomic factors (Mutuo et al. 2005). However, quantitative information on above and belowground C inputs in agroforestry systems is limited (Murthy et al. 2013; Cardinael et al. 2018), particularly in the drylands. The majority of available studies have focused on the humid and sub-humid tropics while the agroforestry systems in the dryland have a significant share (Jama and Zeila, 2005). The dryland ecosystem comprises 40% of the global land mass while it covers 65% in Africa and 50 - 70% in Ethiopia (Jama and Zeila, 2005). Agroforestry practices are major

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features of the land-use systems in the drylands of Eastern and Central Africa (Jama and Zeila, 2005). Trees are used for a variety of purposes in both cropped lands and in livestock grazing systems in the drylands. A climate resilient green economy (CRGE) has been the strategy of Ethiopia's government to build a zero-net carbon economy by 2025 (FDRE 2011). Climate-smart agricultural practices (CSAP) are one of the CRGE strategies for reducing atmospheric concentrations and emissions of carbon dioxide through improved carbon sequestration and storage, respectively and thus achieving sustainable development (Yirgu et al. 2013**)**. However, baseline data on the carbon accumulation potential of local farming practices such as the *Rhamnus prinoides* agroforestry that enable informed decisions are limited. The study on the carbon sequestration and storing potential of *R. prinoides*-based agroforestry could serve as leverage to get the attention of policymakers and development organizations to be considered as one of the CSAPs that should be developed and scaled up. In addition, it could indicate the importance of local practices' contribution to fulfilling the national goal of carbon emission reduction and the need for due consideration in national carbon auditing. Likewise, it will be important to evaluate whether the *R. prinoides* agroforestry system carbon accumulation suffices for carbon certification and concession schemes to better incentivize practicing farmers and improve its sustainability.

Rhamnus prinoides-based agroforestry in the drylands of Tigray region, northern Ethiopia, is an age-old farming practice. *R. prinoides* is an important source of income for subsistence farmers and a business commodity for retailers, exporters, and local beer brewers. Planting *R. prinoides* trees/shrubs at varied spatial arrangements on crop fields and cultivating a variety of cereal crops rotationally under its canopy is a common practice by smallholder farmers in eastern and central Tigray. Farmers propagate *R. prinoides* by collecting seeds from best-performing trees on their own or neighbors' farms. *R. prinoides* agroforestry is used as a means to diversify and maximize production from small land by the smallholding farmers. Farmers partially harvest the matured leaves of *R. prinoides* two to three times a year for sale and home consumption from fourth year of planting up to 50 years. This farming and utilization system of *R. prinoides* is peculiar in Tigray. Most farmers do allocate the best and large share of their farm plots for *R. prinoides* agroforestry in the area.

Biomass is an important variable in estimating the amount of carbon that plants can sequester when they grow or emit when they are cut. Thus, reliable and accurate biomass estimates are required.

Determining trees/shrubs biomass by allometric equations, statistical models that relate plant biomass to some tree futures that are easy to measure is a common method (Chave et al. 2014). There are general models for multispecies and single species developed based on data from multiple sites and local models for multispecies and single species developed based on data from one site. Generally, local models result less bias than general models (Feyisa et al. 2016), because tree growth characteristics are affected by local geographical conditions such as climate, soil properties, altitude, and land-use history (Yuen et al. 2016). Although local models are expensive to develop and may have limited use outside the site where developed, there are attempts to develop local species-specific allometric models to estimate the biomass of trees/shrubs. However, there is no species-specific general or local model developed yet for *R. prinoides* to determine its aboveground biomass (AGB) and belowground biomass (BGB).

It is anticipated that with the increasing density of intercropped trees, overall biomass production per unit area of the agroforestry system will be greater, which in turn promotes biomass C storage. Increased biomass production of trees over time within an agroforestry systems can enhance above and belowground C input to the soil, thereby increasing the formation and accumulation of SOC (Fontaine et al. 2007). Greater tree density in agroforestry system might increase SOC through their positive effects on biomass C input (Saha et al. 2009). Furthermore, the effect of agroforestry practices on SOC may change with soil depth (Cardinael et al. 2018), because trees tend to grow more roots into deeper soil layers, which, in turn, results in higher inputs of organic matter to deeper soil layers (Nair et al. 2010). Moreover, the productivity of agroforestry could vary with tree density. Greater benefits might be gained from trees integrated at an appropriate density through tree produced and synergistic effects on the annual crops (Singh et al. 2007).

The main objective of this study was to estimate the biomass and soil carbon stock of *R. prinoides*-based agroforestry practice in the drylands of northern Ethiopia. Specifically, this study aimed (1) to develop species-specific local AGB and BGB allometric equations (2) to quantify the above and belowground biomass carbon stocks in *R. prinoides*-based agroforestry practice; (3) to estimate soil organic carbon stock in *R. prinoides*-based agroforestry practice and (4) to examine the implication of planting density on carbon stock and farm productivity in *R. prinoides*-based agroforestry.

7.2 Methodology

7.2.1 Sampling Strategy

Stratified random sampling was employed to select inventory and soil sampling farm plots in each site. Farmlands with varied densities of *R. prinoides* plantation at mature stage i.e. dense (< 4 m), medium (4 - 6 m), and sparse (> 6 m) (with canopy cover of > 45%, 30 - 45% and < 30%, respectively) were identified in each site. From the identified farmland with sparse, medium, and dense *R. prinoide* trees, three farm plots from each density group and site were randomly selected. Inventory plots (20 x 20 m) were laid out on the randomly selected farmlands with *R. prinoides* intercropping. Alongside every inventory plot, other 20 x 20 m plots were laid out on farmland without trees/shrubs (open) 10 m far from canopy ends for soil sampling.

7.2.2 Inventory and Biomass Measurement

In each farm plot with *R. prinoides* plantation, inventory of diameter at stump height (DSH) at 30 cm above surface level using diameter tape, total tree height (Ht) from surface to the top of the tree using height measuring stick, and average crown diameter (CD) of wider and narrower side using meter tape was conducted. Trees with sprouts below 30 cm above the surface level were considered as multi-stem and each stem was treated as individual, and measurements were taken for each stems. We considered all divides or sprouts below 30 cm (stump height) from surface level as stem. For the divides above 30 cm, the one with a larger diameter was considered a stem while the one with a lower diameter was a branch.

Allometric equations were developed using a destructive method to estimate biomass. After the inventory was conducted, the overall DSH classes of *R. prinoides* plantation were specified to select representative sample trees for destructive measurement. For the development of the allometric model, a total of 11 *R. prinoides* trees with 27 stems were selected for destructive sampling from three DSH classes proportionally that is six from ≤ 5 cm, fifteen from 5-10 cm and six from ≥ 10 cm. Trees felled from the surface level using handsaw and uprooted by hand digging the soil following the rooting architecture and depth until it reaches less than 1 cm in diameter. After cutting and uprooting the aboveground biomass was divided as stem, branches and leaves and the belowground biomass as main and lateral or branch root of each tree. Stems, branches and roots were crosscut to manageable pieces for fresh weight measurement. Tree components were weighted fresh at field using mechanical hanging balance with an accuracy of 0.1kg separately and one representative subsample with mix of lower, middle and upper parts from each component was taken and weighted its fresh matter at field using sensitive balance with an accuracy of 1g. Sub sample of each component was oven dried at 75ºC until constant weight recorded for three consecutive measurements every day (24 hours) to calculate the dry matter weight ratio.

Three sample disks were taken from each stem from lower, middle and upper parts for wood density (WD) measurement. Samples were debarked and weighted fresh at the field using sensitive balance with an accuracy of 1g. Each disk was immersed into partially water filled glassware with volumetric scales and green volume of each sample was measured through the displacement methods. Samples were oven dried at 75ºC until constant weight recorded for three consecutive measurements every day (24 hours) to obtain the dry matter.

Stem based data was used to develop AGB models while tree based data was used to develop BGB models. For trees with multiple stems, tree based DSH and CD were calculated from square root of the sum square of DSH and CD of stems while tree based Ht and WD were the average of the stems of a tree.

7.2.3 Biomass Data Analysis

The total aboveground biomass (AGB) and total below ground biomass (BGB) for each plant were calculated as a sum of the biomass of all the components. Means and standard deviations for the specific wood density values were calculated for each section per plant and for all plants parts combined. The data were examined for normality and homogeneity. Correlation analysis between dependent variables (biomass components) and independent variables (DSH, Height, CD and WD) was carried out. The scatter plots of AGB and BGB versus the potential predictor variables indicated both linear and nonlinear relationships. Hence, both linear and polynomial regression functions were tested. Since, DSH was the variable having the highest correlation with AGB and BGB in this study, different model forms were formulated for testing using DSH as the sole predictor and combined with a stepwise inclusion of Ht, CD, and WD. The following models with significant parameter estimates ($P < 0.05$) were selected;

$$\mathrm{AGB} = \mathrm{a} + \mathrm{b} * \mathrm{DSH} \qquad 7.1$$

$$\mathrm{AGB} = \mathrm{a} + \mathrm{b} * \mathrm{DSH} + \mathrm{c} * \mathrm{Ht} \qquad 7.2$$

$$\mathrm{AGB} = \mathrm{a} * \mathrm{DSH}^{b} \qquad 7.3$$

$$\mathrm{AGB} = \mathrm{a} * \mathrm{DSH}^{\mathrm{b}} * \mathrm{Ht}^{\mathrm{c}} \qquad 7.4$$

$$\mathrm{AGB} = \mathrm{a} * \mathrm{DSH}^{\mathrm{b}} * \mathrm{CD}^{\mathrm{c}} \qquad 7.5$$

$$\mathrm{BGB} = \mathrm{a} + \mathrm{b} * \mathrm{DSH} \qquad 7.6$$

$$\mathrm{BGB} = \mathrm{a} * \mathrm{DSH}^{\mathrm{b}} \qquad 7.7$$

$$\mathrm{BGB} = \mathrm{a} * \mathrm{DSH}^{\mathrm{b}} * \mathrm{Ht}^{\mathrm{c}} \qquad 7.8$$

where AGB is total aboveground tree biomass (Kg), DSH is diameter at stump height (cm), Ht is total tree height (m), and CD is crown diameter (m) and a, b and c are parameter estimates.

The proposed models were evaluated according to adjusted determination coefficient (adjusted R^2), F test, mean square error (MSE), root mean square error (RMSE), mean predicted error (MPE), variance inflation factors (VIF), the predicted residual and the biologic logic of the model and akaike information criterion (AIC). Leave-one-out-cross validation (LOOCV) procedure (James et al. 2013) was used to determine RMSE and MPE. This procedure leaves one observation for validation, and the remaining n-1 observations for model calibration. The excluded observation was predicted and the error was computed. The procedure was repeated n times until every observation has been left out and predicted. The n errors were used to calculate MSE, RMSE and MPE.

In addition, previously developed five multispecies and three species-specific models by Tumwebaze et al. (2013), Segura et al. (2006), Negash et al. (2013) and Ubuy et al. (2018) for agroforestry systems in east Africa and exclosure areas in Tigray, northern Ethiopia were applied on this study dataset and performed a t-test on the MPE values if they were significantly different from zero ($P < 0.05$). Since, people used to adopt allometric models to estimate biomass in agroforestry systems with single and/or multiple tree species, testing models developed for multispecies and species-specific could help to compare the level of bias in biomass estimation.

To develop the species-specific allometric equation R software packages were used to run regression analysis. The allometric model with better score on the evaluation criteria SSM4 and SSM8 (Table 7.1) were used to estimate aboveground and belowground biomass respectively. Prediction of stem based AGB and tree based BGB was done based on the inventory data. The sum of stem based AGB and tree based BGB estimates in inventory plots (20x20 m) were converted into hectare basis. Biomass stock was converted into carbon stock by multiplying the default carbon fraction of 0.47 (IPCC 2006).

7.2.4 Soil Analysis

Composite soil sample from four corner and one center was taken from farm plots with varied *R. priniodes* intercropping density and nearby farms (> 10 m far from canopy ends) without any tree/shrub plants (open) at two soil depths (0 - 30 cm and 30 - 60 cm). Hence, the total soil sample from three study sites with three replications from each density and respective open was 108 (54 from each soil depth). Before chemical analysis, the collected samples were air dried, then ground and sieved to separate the < 2 mm fraction. Composite soil sample were analyzed for soil organic carbon (SOC) content using Walkley-Black method and soil texture (hydrometric method) following procedures stated in (Van Reeuwijk 2008).

Undisturbed soil sample was taken using core sampler with 100 cc from all farm plots at one randomly selected sampling point from upper and lower soil depth for the examination of bulk density. The total number of the undisturbed soil sample was also108 from the study sites.

Undisturbed soil samples were analyzed for bulk density (BD) by weighing oven dried at 105°C soil samples with known volume (Brady and Weil 2002). Since the presence of rock fragments leads to over or under estimate SOC stock (Throop et al., 2012), gravel fractions with > 2mm were separated from each sample and BD was adjusted accordingly.

Soil organic carbon (SOC) stock was computed following Grimm et al. (2008) and Throop et al. (2012) equation:

$$\text{SOC stock } (\text{Mg ha}^{-1}) = \text{SOC cont } (\%) * \text{BD } (\text{g cm}^{-3}) * \text{SD } (\text{cm}) \qquad 7.9$$

where SOC stock is soil organic carbon stock (Mg ha^{-1}), BD is the bulk density of soil without gravel fraction >2mm (g cm^{-3}), SOC cont is soil organic carbon content (%) and SD is soil depth (cm).

Factorial two-way analysis of variance (ANOVA) was employed to compare the difference in soil organic carbon content and SOC stock on farms with varied *R. priniodes* intercropping density (sparse, medium and dense) and nearby farms without trees/shrubs (open) at different soil depth using R software package.

7.3 Results

7.3.1 Aboveground and Belowground Biomass Models for *R. prinoides* in the Drylands

The wood density of the sample trees was 0.615 g cm^{-3} in average. The height varied between 1.5 and 5.5 m, DSH between 4.0 and 13.3 cm, CD between 1.4 and 3.8 m and total aboveground biomass between 2.7 and 31.8 Kg. The distribution of total aboveground biomass among biomass components was stem 56.9%, branches 37.6%, and leaves 5.5%. The total aboveground biomass of *R. prinoides* presented a high correlation with DSH ($r = 0.91$; $P < 0.001$) and with Height ($r = 0.83$; $P < 0.001$) (Fig. 4) followed by CD ($r = 0.73$; $P < 0.01$) while poorly correlated with WD ($r = 0.077$).

The total belowground biomass of sample trees ranges between 5.5 and 27.5 Kg (Figure 7.1). The distribution of total belowground biomass among biomass components was main root 72.5% and root branches 28.5%. The average belowground biomass to aboveground biomass ratio of *R. prinoides* sample trees was 0.57. The total belowground biomass of *R. prinoides* presented a high correlation with DSH ($r = 0.9$; $P < 0.001$) and Height ($r = 0.78$; $P < 0.001$) (Fig. 4) followed by CD ($r = 0.68$; $P < 0.01$) while poorly correlated with WD ($r = 0.085$).

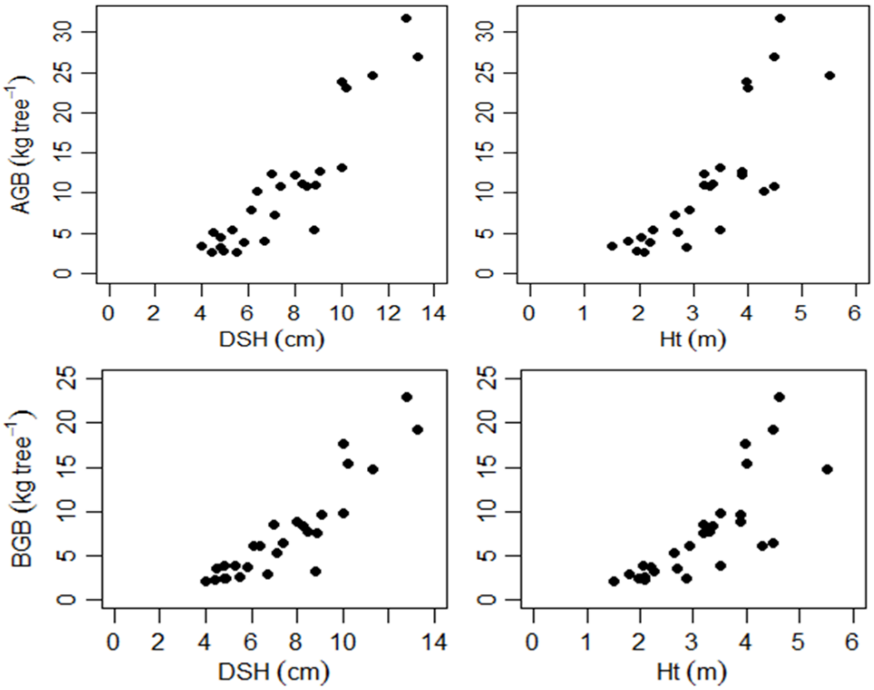

Figure 7. 1 Relationship of total aboveground (AGB) and belowground (BGB) biomass with tree diameter at stump height (DSH) and total tree height (Ht)

The models for estimating the total aboveground biomass based on DSH and/or Height presented good fit ($0.82 < R^2 < 0.93$). The allometric equation SSM4 (Table 7.1), with power function that include DSH and Ht in its all variables, is the best predictor of the total aboveground biomass in *R. prinoides* plants presenting the highest R^2 and the lowest MSE, RMSEP, MPE, RSE and AIC values followed by SSM2 and SSM3.

The models for estimating the total belowground biomass based on DSH and Height presented good fit ($0.84 < R^2 < 0.90$). The allometric equation SSM8 (Table 7.1), with power function that include DSH and Ht in its all variables, was the best predictor of the total belowground biomass in *R. prinoides* plants presenting the highest R^2 and the lowest MSE, RSE and AIC values followed by SSM7 that include DSH alone.

Table 7. 1 Species specific (*R. prinoides*) local above and belowground biomass models developed with different combination of tree variables (DSH, Ht and CD)

Models	Equations	R^2	MSE	RMSEP		MPE		AIC
				(Kg)	(%)	(Kg)	(%)	
SSM1	$AGB = -11.2 + 2.9 * DSH$	0.83	13.4	3.66	33.7	0.069	0.63	148
SSM2	$AGB = -13.8+2.1*DSH+2.6*Ht$	0.87	10.9	3.3	30.4	-0.002	-0.02	141.6
SSM3	$AGB = 0.146* DSH^{2.074}$	0.86	12.4	3.52	32.4	-0.058	-0.53	143
SSM4	$AGB = 0.182*DSH^{1.462}*Ht^{0.870}$	0.92	7.67	2.77	25.5	-0.059	-0.54	130.5
SSM5	$AGB = 0.15*DSH^{1.77}*CD^{0.63}$	0.89	8.7	3.2	27.3	-0.067	-0.67	148.7
SSM6	$BGB = 2 + 0.189*DSH$	0.81	6.3	3.2	33.4	-0.08	-0.07	129.5
SSM7	$BGB = 0.146*DSH^{2.042}$	0.85	5.94	2.44	31.6	-0.01	-0.08	123.8
SSM8	$BGB = 0.133*DSH^{1.596}*Ht^{0.618}$	0.89	5.84	2.42	31.4	-0.13	-1.72	118.7

SSM is species specific model, AGB is total aboveground biomass, BGB is total belowground biomass, DSH is tree diameter at stump height (cm), Ht is total tree height (m). R^2 coefficient of determination, MSE is mean square error, RMSE is root mean square error and MPE is mean prediction error. Models presented are with parameter estimates significantly ($p<0.05$) different from zero.

Existing models were tested in this study dataset (Table 7.2). When tested for all observations ($n=27$), all multispecies models developed by Tumwebaze et al. (2013) for trees in agroforestry systems and Ubuy et al. (2018) for trees in exclosures significantly over predicted the measured aboveground biomass while two of the specific models developed for *Coffea arabica* and *Casuarina equisetifolia* in agroforestry system by Segura et al. (2006) and Tumwebaze et al. (2013) respectively significantly under predicted the aboveground biomass. When the species-specific model developed for *Coffea arabica* in agroforestry system by Negash et al. (2013) tested, the mean predicted errors (MPEs) was not significantly different from zero.

Table 7. 2 Observed biomass (Kg) and mean predicted error (MPE) of existing models tested on this study dataset (n = 27).

Model type	Reference	Independent Variable	N	Observed (kg)	Predict mean error (MPE)	
					(kg)	(%)
Multi-species	Tumwebaze et al. (2013)	Ht	57	10.85	-11.447***	-105.488
	Tumwebaze et al. (2013)	CD	57	10.85	-46.315***	-426.814
	Ubuy et al. (2018)	DSH	305	10.85	-4.159***	-38.326
	Ubuy et al. (2018)	DSH, Ht	305	10.85	-2.9247***	-26.9525
	Ubuy et al. (2018)	DSH, CD	305	10.85	-2.00125**	-18.4425
Species-specific	Segura et al. (2006)	Ht	96	10.85	7.944***	73.211
	Tumwebaze et al. (2013)	Ht	12	10.85	9.322***	85.902
	Negash et al. (2013)	DSH	31	10.85	1.531	14.10495

Independent variables are used by existing models, Ht is total height (m), CD is crown diameter (m), DSH is diameter at stump height (cm), N is number of sample trees of the existing models; ** and *** are mean prediction errors significantly different from zero at 0.01 and 0.001 levels, respectively.

7.3.2 Biomass Carbon Stock in *R. prinoides-based* Agroforestry with varied Density in the Drylands

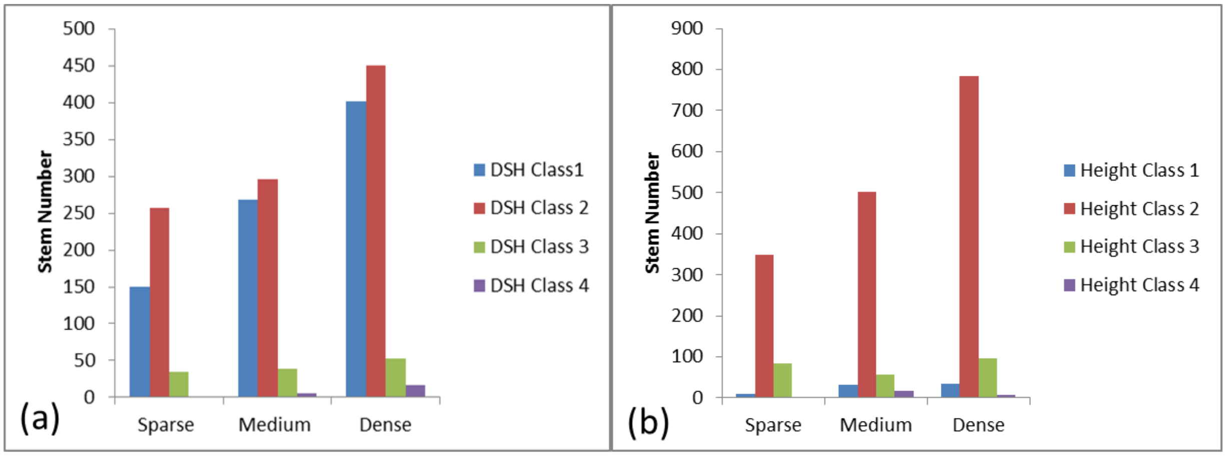

Figure 7. 2 *R. prinoides* tree stem (a) and height (b) size classes distribution in sparsely, medium and densely planted farm plots. DSH classes are 1 = 0-5cm, 2 = 5-10cm, 3 = 10-15cm and 4 > 15cm. Height classes are 1 = 0-2m, 2 = 2 - 4m, 3 = 4-6m and 4 > 6m.

The number of tree stems in each DSH class increased from sparsely to densely planted farm plots while the lower classes 1 and 2 are dominant in all density groups (Figure 7.2 a). Tree stems with higher DSH class are more in the dense farm plots followed by medium plots than sparsely planted farm plots. Likewise, the number of tree stems in height class 2 increased from sparsely to densely planted farm plots and with higher number of stems than the rest classes (Figure 7.2 b).

The aboveground biomass per tree stems in sparsely planted farm plots i.e. 8.34 ± 6.35 Kg was found significantly higher ($P < 0.05$) than the medium and densely planted with similar mean biomass stock i.e. 7.43 ± 7.29 Kg and 7.55 ± 8.11 Kg respectively. Likewise, the belowground biomass per tree stems in sparsely planted farm plots i.e. 5.67 ± 4.4 Kg was found significantly higher than the medium and densely planted biomass i.e. 5.26 ± 5.0 Kg and 5.4 ± 5.7 Kg respectively.

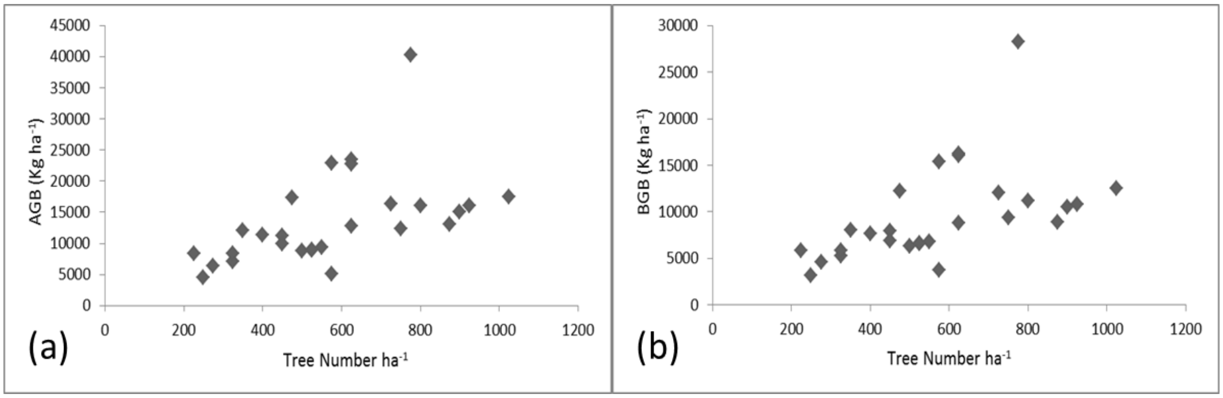

Figure 7. 3 Relationship of aboveground biomass (AGB) (a) and belowground biomass (BGB) (b) with tree density in farm plots with *R. prinoides-based* agroforestry

Overall the aboveground biomass increased from farm plots with lower to higher tree density while there were some farm plots with higher AGB than farm plots with similar and higher tree density (Figure 7.3a). Likewise, the belowground biomass increased from farm plots with lower to higher tree density in most cases while there are some farm plots with higher BGB than farm plots with similar and higher tree density (Figure 7.3b).

The average biomass stock in *R. prinoides* agroforestry was 29.41 Mg ha^{-1} (Table 7.3) that was 20.83, 26.53 and 40.87 Mg ha^{-1} in the sparsely, medium and densely planted farms respectively. The average aboveground biomass stock in the *R. prinoide* based agroforestry practice was 17.66 Mg ha^{-1} (Table 7.3) that was 12.53, 15.96 and 24.49 Mg ha^{-1} in the sparsely, medium and densely planted farms, respectively. The average belowground biomass stock in *R. prinoides* agroforestry practices was 11.75 Mg ha^{-1} (Table 7.3) that was 8.30, 10.57 and 16.38 Mg ha^{-1} in the sparsely, medium and densely planted farms respectively. The average belowground biomass stock was lower by 5.91 Mg ha^{-1} (33.46%) than the average aboveground biomass stock.

Table 7. 3 Estimate of biomass and carbon stock in *R. prinoides* agroforestry practice with varied density in the drylands

Tree Density	Canopy Cover (%)	Basal Area (m^2 ha^{-1})	Aboveground		Belowground		Total	
			Biomass Stock (Mg ha^{-1})	Carbon stock (Mg ha^{-1})	Biomass Stock (Mg ha^{-1})	Carbon stock (Mg ha^{-1})	Biomass stock (Mg ha^{-1})	Carbon Stock (Mg ha^{-1})
Sparse	27.24	3.63	12.53	5.89	8.30	3.90	20.83	9.79
Medium	33.83	4.56	15.96	7.50	10.57	4.97	26.53	12.47
Dense	50.32	7.04	24.49	11.51	16.38	7.70	40.87	19.21
Average	36.14	5.21	17.66	8.30	11.75	5.52	29.41	13.82

The average biomass carbon stock in *R. prinoides* agroforestry was 13.823 Mg ha^{-1} (Table 7.3) that was 9.79, 12.47 and 19.21 Mg ha^{-1} in the sparsely, medium and densely planted farms, respectively. The average aboveground biomass carbon stock was 8.300 Mg ha^{-1} (Table 7.3) that was 5.89, 7.50 and 11.51 Mg ha^{-1} in the sparsely, medium and densely planted farms, respectively. The average belowground biomass carbon stock was 5.52 Mg ha^{-1} (Table 7.3) that was 3.90, 4.97 and 15.26 Mg ha^{-1} in the sparsely, medium and densely planted farms respectively. The average belowground biomass carbon stock was lower by 2.78 (33.46%) than the average aboveground biomass carbon stock.

7.3.3 Soil Organic Carbon Stock in *R. prinoides*-based Agroforestry with varied Planting Density in the Drylands

The texture of the soils in farmland with *R. prinoides* intercropping at varied density (sparsely, medium and densely) and nearby farmland without trees/shrubs was similar. In addition, the texture of soils was similar through the soil depth in farmlands with *R. prinoides* at varied density and without trees/shrubs (Table 7.4). The bulk density of the soils in farmland with *R. prinoides* intercropping at varied density and nearby farmland without trees/shrubs was similar. In addition, the bulk density of soils was similar through the soil depth in farmlands with *R. prinoides* at varied density and without trees/shrubs (Table 7.4).

Table 7. 4 Soil carbon stock in farms with *R. prinoides* agroforestry at varied density and nearby farms without trees (open)

Variable	Soil depth(cm)	*R. prinodes* planting density				Open
		Sparse	Medium	Dense	Average	
Sand (%)	Upper (0-30)	29.00±17.32^{aA}	32.33±4.16^{aA}	43.0± 6.93^{aA}	34.8±11.5^{aA}	35.4±6.5^{aA}
	Lower (30-60)	43.67±12.22^{aA}	45.67±12.7^{aA}	44.3±5.03^{aA}	44.6±9.2^{aA}	34.7±7.5^{aA}
	Overall (0-60)	36.33±15.63^{a}	39.00±11.17^{a}	43.67±5.47^{a}	39.7±11.3^{a}	35± 6.8^{a}
Silt (%)	Upper (0-30)	57.67±16.04^{aA}	53.67±10.26^{aA}	45.00±9.17^{aA}	52±12^{aA}	51.67±6.9^{aA}
	Lower (30-60)	43.0±8.0^{aA}	44.33±2.31^{aA}	45.0±11.14^{aA}	44±7^{aA}	47.9±8.13^{aA}
	Overall (0-60)	50.33±13.10^{a}	49.0±8.39^{a}	45.0±9.12^{a}	48±10.4^{a}	49.8±7.6^{a}
Clay (%)	Upper (0-30)	13.33±7.57^{aA}	14.00±6.93^{aA}	12.00±3.46^{aA}	13±7^{aA}	12.9±5.7^{aA}
	Lower (30-60)	13.33±4.62^{aA}	1.00±10.39^{aA}	10.67±8.33^{aA}	11±5.5^{aA}	17±7.8^{aA}
	Overall (0-60)	13.33±5.6^{a}	12.00±8.2^{a}	11.33±5.75^{a}	12±6^{a}	15±7^{a}
BD (g cm^{-3})	Upper (0-30)	1.25±0.15^{aA}	1.24±0.08^{aA}	1.19±0.13^{aA}	1.2±0.1^{aA}	1.18±0.1^{aA}
	Lower (30-60)	1.24±0.07^{aA}	1.23±0.11^{aA}	1.16±0.11^{aA}	1.21±0.1^{aA}	1.2±0.1^{aA}
	Overall (0-60)	1.25±0.1^{a}	1.23±0.1^{a}	1.17±0.12^{a}	1.2±0.1^{a}	1.18±0.1^{a}
SOC (%)	Upper (0-30)	1.3±0.9^{aA}	2.01±0.7^{bA}	2.13±1.4^{bA}	1.8±0.9^{aA}	1.6±0.8^{aA}
	Lower (30-60)	1.17±0.8^{aA}	1.618±0.65^{bA}	1.9±1.25^{cA}	1.6±0.7^{bA}	1±0.6^{aB}
	Overall (0-60)	1.24±0.85^{a}	1.79±0.7^{b}	2.0±1.3^{c}	1.7±0.8^{b}	1.3±0.7^{a}
SOC stock (Mg ha^{-1})	Upper (0-30)	49.3±36.3^{aA}	72.4±24.6^{aA}	77.6±57.7^{aA}	66.4±33^{aA}	56± 25.9^{aA}
	Lower (30-60)	43.0±29.6^{aA}	58.5±21.2^{bA}	65.0±46.5^{bA}	55.5±24.5^{bA}	37.1±22^{aB}
	Overall (0-60)	93.2±32.5^{a}	130.9±23.6^{b}	142.6±51.6^{b}	121.9±29^{b}	93.2±25.6^{a}

Values followed by the same superscripts are not significantly different along rows (lowercase) and along columns (uppercases) at $P < 0.05$ based on LSD test

The soil organic carbon (SOC) content in farms with *R. prinoides* intercropping (1.7±0.8%) is significantly higher than nearby open farms (1.3 ± 0.7%). SOC content wasn't significantly decreasing in farms with *R. prinoides* intercropping at varied density from upper to lower soil depth while it was significantly decreasing in the open farms (Table 7.4). SOC content was significantly increased as the density of *R. prinoides* planting increased. The soil organic carbon stock in farms with *R. prinoides* intercropping (121.9 ± 29 Mg ha^{-1}) was significantly higher than nearby open farms (93.2 ± 25.6 Mg ha^{-1}). However, SOC stock in the sparsely planted farms were similar with open farms and significantly lower than farms with medium and densely planted. SOC stock was significantly decreasing from upper to lower soil depth in the open farms while there were no significant differences in farms with *R. prinoides* intercropping at varied density (Table 7.4).

7.4 Discussion

7.4.1 Species Specific Aboveground and Belowground Biomass Models for *R. prinoides* in *R. prinoides-based* Agroforestry in the Dryland

Simple model with one independent variable and easy to measure like SSM3 and SSM7 (Table 7.1) is more practical. Many authors (Kanninen and Pe´rez 2002; Segura and Kanninen 2005) have developed models using DBH as a predictor of total aboveground biomass for other species. Determining tree/shrub biomass by allometric equations using DBH and height has become preferable method in many forest biomass studies (Chave et al. 2014). In this study, DSH and height showed strong relationships with the total aboveground biomass. As a result, allometric models developed using DSH alone and in combination with height and crown diameter showed good fit and provide consistent estimation of aboveground biomass. Thus, SSM4 with relatively better fit that explained 92% of the variance in measured AGB and produced the lowest average relative error (-0.059) was used to estimate the above ground biomass while all selected models for AGB (Table 7.1) might be applied to estimate AGB of *R. prinoides* in rain-fed farming system. Using DSH and Ht together as predictor may increase model robustness, as it can help to capture the effects of site specific DSH and Ht relationship on biomass allometric equations (Valbuena et al. 2016).

In addition, DSH and height showed strong relationships with the total belowground biomass. Drexhage and Colin (2001) stated that root weight of individual trees can be estimated from stem diameter. Accordingly, allometric models developed using DSH alone and in combination with height (Table 7.1) showed good fit and provide consistent estimate of belowground biomass. Hence, SSM8 with relatively better fitness that explained 89% of the variance in measured BGB and produced the lowest average relative error (-0.13) was used to predict belowground biomass stock while all selected allometric models for BGB (Table 7.1) can be applied to estimate BGB of *R. prinoides* in rain-fed farming system of the drylands. These models are practical, as DSH and height can be easily measured in the field. However, their application for plants in different agro-ecology and management system with different characteristics and architecture should be validated with local data.

Compared to the previously developed multispecies and species-specific biomass estimation models tested in this study dataset, the developed species-specific allometric equation (SSM4) produced the lowest prediction error (MPE) for *R. prinoides*. Existing multispecies models developed for agroforestry and exclosures were significantly over predicted the observed AGB of *R. prinoides* while most of the species specific models developed for other species in agroforestry system under predict (Table 7.2). The higher bias of existing multispecies and species-specific models might be resulted from low representation of *R. prinoides* size (DSH, Ht and CD) classes while SSM4 able to capture the diversity of sizes classes of *R. prinoides* plantation. This is in line with many study reports that stated site and species-specific biomass estimation allometric equations are more accurate and reliable to convert forest inventory data to AGB (Feyisa et al. 2016 and Yuen et al. 2016). Thus, the developed model SSM4 could play a considerable role in reducing biomass estimation uncertainties, which resulted from the low representation of species-specific trees size class distribution. The fact that there wasn't previously developed species-specific biomass model for *R. prinoides* made the developed model more important.

7.4.2 Aboveground and Belowground Biomass and Carbon Stock in *R. prinoides*-based Agroforestry with varied Density in the Dryland

The aboveground biomass (AGB) stock in densely planted farm plots is higher by 11.956 Mg ha^{-1} (95%) and 8.53 Mg ha^{-1} (53%) than sparsely and medium planted farm plots, respectively. The average AGB per tree is significantly higher ($P < 0.05$) in sparsely planted than medium and densely planted farm plots. This showed that the higher biomass in the densely planted farm is resulted from the higher number of trees than the size of trees. In line to this Takimoto et al. (2008) reported higher biomass stock in agroforestry systems with higher tree number. However, the higher AGB in some plots with medium tree density (Figure 7.3a) than plots with similar and higher number of trees indicated that tree size resulted in increased biomass stock. Likewise, the increased belowground biomass with increased planting density of *R. prinoides* (Figure 7.3b) indicated that tree density is contributing more to the BGB stock than tree size. The BGB stock of *R. prinoides* in the densely planted farms were found higher by 8.08 Mg ha^{-1} and 5.81Mg ha^{-1} than sparsely and medium planted farm plots, respectively.

The belowground biomass accounts 39.95% of the estimated total biomass of 29.41 Mg ha^{-1} in the *R. prinoides* agroforestry. Variation in site condition and management system could affect biomass distribution (Newaj et al. 2013; van Noordwijk et al. 2015). The belowground to aboveground biomass ratio (0.57) of *R. prinoides* is higher than 40% for agroforestry trees (Young et al. 1987) and the IPCC range (0.24 - 50%) for the tropics while it is within the range stated for the drylands that is 0.2 - 0.63% (Sanquetta et al. 2011; Costa et al. 2014). Joyce and Birdsey (2000) indicated that changing agro-climate may affect ecosystem productivity and allocation of above-ground versus below-ground biomass. The dryland agro-ecology where *R. priniodes* is growing in rain-fed intercropping and the management system may contribute to the increased root biomass ratio.

R. priniodes might invest on its rooting system for best use of scarce resources to tolerate harvesting pressure, competition from crops and moisture stress that comply with observations by van Noordwijk et al. (2015) for agroforestry system. These are in line with the arguments that root to shoot ratio vary with site condition, stand density, time span and silviculture (Costa et al. 2014). The main purpose of *R. prinoides* planting on crop fields in the study area is for partial harvest of its leaves two to three times a year to ensure continuous regeneration and production. This may contribute for the relatively lower share of aboveground biomass. The contribution of leaves in the AGB estimation was 5.5% while *R. prinoides* is dense thick evergreen tree/shrub (Orwa et al. 2009) selected for its foliage production and regeneration capacity after frequent partial harvest of its leaves.

The estimated biomass carbon stock (13.82 Mg ha $^{-1}$) of *R. prinoides*-based agroforestry in the drylands is significant addition compare to treeless farming systems in the region. The biomass carbon stock in *R. prinoides* agroforestry is comparable to the estimated total potentials reported by Matocha et al. (2012) and Mbowet et al. (2014) for different agroforestry practices in the drylands. Moreover, the biomass carbon stock in farms with *R. prinoides* is relatively higher than reports from different land use systems in the region. The AGB carbon stock in farms with *R. prinoides* is similar to AGB carbon stock 9.08 ± 1.44 Mg C ha^{-1} and higher than 4.01 Mg ha^{-1} of exclosures reported by Gessesse (2016) and Mokria et al. (2018) respectively. It is also higher than AGB carbon stock in rangelands 1.49 ± 0.18 Mg ha^{-1} and 2.1 Mg ha^{-1} reported by Gessesse (2016) and Mokria et al. (2018), respectively. The belowground biomass (BGB) carbon stock in farms with *R. prinoides* is higher than BGB carbon stock in exclosure (3.16 ± 0.39 Mg ha^{-1}) and rangelands (3.67 ± 0.06 Mg ha^{-1}) reported by Gessesse (2016). The total biomass carbon stock in farms with *R. prinoides* is comparable with the carbon stock in exclosure forests (22.29 Mg ha^{-1}) and higher than rangelands carbon stock (7.76 Mg ha^{-1}) while lower than protected forests carbon stock (58.11 Mg ha^{-1}) reported by Solomon et al. (2017). The carbon stock in the *R. prinoides* agroforestry that is comparable with the stocks in exclosures and rangelands in the region may indicate that agriculture is not only emitter but also can improve the sequestration and storage of carbon, if transformed and managed in to climate smart practices.

7.4.3 Soil Organic Carbon Stock in *R. prinoides*-based Agroforestry with varied Density in the Drylands

Soil organic carbon content (SOC) was found significantly higher in farms with *R. prinoides* intercropping than farms without trees/shrubs. Likewise, SOC significantly increased as *R. prinoides* density increased. SOC content was found not significantly decreasing with increasing soil depth in farms with *R. prinoides* at varied density while significantly decreased in farms without trees/shrubs. The less significant SOC difference across soil depth in farms with *R. prinoides* intercropping at varied density is in line with Nair et al. (2010) and Kell (2012) observation that agroforestry systems store more C in deeper soil layers near trees than away from trees while in contrary with Chibsa and Ta'a (2009) report for different land-uses. The less significant difference across soil depth in farms with *R. prinodes* might be attributed to the fine root turnover from the root system in the lower soil depth. The overall significantly higher SOC content by 0.4% in farm with *R. priniodes* than open is attributed to the contribution of *R. prinodes* as perennial tree or shrub. Higher SOC pools in agroforestry systems can be particularly achieved by increasing the amount of biomass C returned to the soil and by strengthening soil organic matter stabilization or by decreasing the rate of biomass decomposition (Sollins et al. 2007; Rasse et al. 2005).

SOC stock was found significantly higher in farms with *R. prinoides* intercropping than open farms. However, the SOC stock in sparsely planted farm was found similar with open farms. The higher SOC stock in farm with medium to densely planted farms attributed to the significantly higher SOC content because both farm types had similar soil texture, BD and same soil depth. The higher SOC stock in farms with *R. prinoides* is expected considering the augmenting role of agroforestry on the soil carbon content (Sollins et al. 2007; Rasse et al. 2005). The soil organic carbon stock in *R. prinoides* agroforestry (121 Mg ha^{-1}) is similar to the estimated total potentials reported by Matocha et al. (2012) and Mbowet et al. (2014) for different agroforestry practices. Moreover, the soil organic carbon stock in farms with *R. prinoides* is similar to the stock in exclosure and rangelands reported by Gessesse (2016) in the region.

SOC stock was not significantly decreasing with increasing soil depth in farm with *R. prinoides* at varied density in contrary Chibsa and Ta'a (2009) report for different land uses while significantly decreased in farms without trees/shrubs. The large belowground biomass (39.9 % of the total) may contribute to the higher carbon stock in the lower soil depth from its exudates and litter falls. The higher SOC stock in lower soil depth in farms with *R. prinoides* is in line with Nair et al. (2010) and Kell (2012) observation that agroforestry systems store more C in deeper soil layers near trees than away from trees. Overall, 42.8% of the total SOC stock was found in the soil horizon 30 - 60 cm, with 39.8% and 45.9% in the subsoil of open farms and farms with *R. prinoides* intercropping respectively. Potential of SOC stock across soil depth indicates the importance of considering soil depths below the topsoil.

7.5 Conclusion

This study provides new species-specific biomass allometric model for *R. prinoides* and original data on the carbon stock and productivity of *R. prinoides*-based agroforestry practice in the drylands. Species-specific allometric equations developed to predict total aboveground and belowground biomass of *R. prinoides* using diameter at stump height (DSH) and height demonstrated that it is consistent and certain. The higher biomass and soil carbon stock in *R. prinoides* agroforestry than grazing land is an indicator for the possibility of increasing the carbon stock in agricultural farming systems through investment in agroforestry systems. Incorporating optimum number of trees with socioeconomic values such as *R. prinoides* into agricultural fields can be potential for improving carbon sequestration and storage and productivity. In developing countries like Ethiopia with high dependence on agriculture and natural resources, improving carbon stock in farm lands could be potential option to mitigate climate change impacts. Farming systems that incorporates trees/shrubs such as *R. prinoides* agroforestry with potential of carbon stock needs to be explored, appreciated, improved, scaled up and sustained. Agroforestry systems used to play mitigation and adaptation roles and the contribution of *R. prinoides*-based agroforestry in adaptation of climate change impacts needs to be assessed.

Chapter 8 Lessons and Recommendations

8.1 Major Findings and Lessons

Tree-based farming, such as agroforestry, is key to climate-smart agriculture (CSA) development, which integrates productivity, adaptation, and mitigation objectives (Lipper et al. 2014; Thornton et al. 2018). Agroforestry enhances productivity, reduces climate risks, and mitigates climate change by lowering greenhouse gas emissions (Thornton et al. 2018; FAO 2018). Unlike specialized monocultures, vulnerable to climate change, diversified systems with trees provide more stability and reduce risks from extreme events (Gockowski & Asten 2012; Kim et al. 2012).

This study examines the potential of *R. prinoides*-based agroforestry in drylands for CSA, comparing it with mono-cropping systems. It assesses the distribution potential and characteristics of the practice using species distribution modeling (Maxent) and stated attributes for agroforestry classification, respectively. It also evaluates the socioeconomic benefits, and climate change adaptation and mitigation role of *R. prinoides* agroforestry compared to annul crop mono-cropping. The findings highlight how tree-based farming systems offer a more resilient, sustainable alternative to mono-cropping, aligning with CSA goals.

8.1.1 Climate and Farmers' Decision Determine the Distribution and Characteristics of *R. prinoides*-based Agroforestry

This study assessed the distribution and suitability of *R. prinoides*-based agroforestry. The species is primarily found in the highlands and midlands, where conditions such as moderate temperatures, and lower evapotranspiration prevail. *R. prinoides* agroforestry is site-selective, thriving in areas with partial solar exposure and favorable soil conditions. The distribution of this agroforestry practice is influenced by local climate, site conditions, and farmers' decisions, with rain-fed systems in the highlands and irrigation-based systems downstream. This suggests that agroecological suitability and landowner interests play crucial roles in expanding tree-based farming (Harja et al., 2006; Bukomeko et al. 2019). Temperature and precipitation were key factors in predicting the distribution of *R. prinoides* agroforestry. Climate change may reduce the suitable areas for this practice, particularly in the midlands, where rising temperatures could limit its future potential. In line with this finding Odeny et al. (2019) reported that changing environment resulted in higher tree/shrub species richness in the mountainous regions. This highlights the importance of incorporating climate dynamics into land use planning to adapt to changing conditions.

The study also examined the characteristics of *R. prinoides* agroforestry, noting that farmers prefer intercropping *R. prinoides* with annual crops due to its minimal competition, compatibility, and higher-value products. The spatial arrangement of trees, especially row planting, is preferred for its efficiency and compatibility with companion crops. The local harvesting system, which involves partial picking of ripened leaves at different intervals, optimizes productivity. These practices demonstrate that well-designed agroforestry systems with appropriate component arrangements and management techniques can enhance production, efficiency, and sustainability (Lasco et al. 2014; Schroth et al. 2003; Teixeira et al. 2003). Overall, this study emphasizes the need for research on the agroecological and socioeconomic suitability of tree-based farming to ensure its effective scaling and adaptation to future climate scenarios.

8.1.2 Diversifying Production System through the Integration of Trees/Shrubs Improve the Socioeconomic Benefits of Smallholders in the Drylands

This study assessed the socioeconomic benefits of *R. prinoides*-based agroforestry as an alternative production system for enhancing smallholder farmers' well-being. The integration of *R. prinoides* trees/shrubs with annual crops diversifies resource use across space and time, improving yield and income through intensification and commercialization. Agroforestry systems like this can enhance sustainable intensification by providing diverse products, including valuable tree products that contribute to higher incomes (Carsan et al., 2014; Cardinale et al., 2011; Verchot et al., 2007). *R. prinoides* agroforestry was found to be three times more profitable than wheat mono-cropping, with higher labor productivity and fewer seasonal labor issues. Income from *R. prinoides* sales also served as a source of savings, enabling farmers to reinvest in other productive activities. This highlights the potential of tree-based farming to contribute to sustainable intensification and commercialization for smallholder farmers.

Additionally, *R. prinoides* agroforestry created off-season employment opportunities, reducing underemployment and improving labor utilization efficiency. The commercial products of *R. prinoides*, such as for local brewing and retail, further extended its benefits to the wider community. The planting of *R. prinoides* also enhanced land tenure security, offering farmers permanent markers for land use or compensation rights. These could incentivize further adoption of tree-based farming among smallholder farmers.

Regarding gender role in *R. prinoides*-based agroforestry, this study found that females played a larger role in the harvesting and marketing of *R. prinoides* products, reflecting gendered labor divisions common in agroforestry (Kiptot and Franzel 2012). The higher women's involvement in income administration, driven by their role in harvesting, aligns with the concept of labor-creating rights (Volker and Waibel, 2010). This highlights how agroforestry systems can empower women economically and socially, underscoring the importance of considering gender dynamics in the scaling-up of tree-based farming practices. Overall, *R. prinoides*-based agroforestry offers significant socioeconomic benefits, improving farmer incomes, labor efficiency, and land use security, while also contributing to gender equity. Further research on the role of gender and the socioeconomic impacts of tree-based farming is essential for optimizing these systems for broader adoption and sustainability.

8.1.3 Diversifying Production System through the Integration of Trees/Shrubs Enhance Adaptation and Mitigation in the Drylands

This study examined the role of *R. prinoides*-based agroforestry in enhancing climate change adaptation and mitigation. The practice improves resilience to climate variability by diversifying resource use and production seasons. *R. prinoides* agroforestry buffers against rainfall variability by utilizing residual moisture and off-season rainfall, stabilizing production even in dry years. The inverse phenology of *R. prinoides* reduces competition with annual crops, improving overall resources use efficiency and crop growth. As a result, this system stabilizes income and production, helping farmers cope with climate and market variability. Additionally, *R. prinoides*-based agroforestry offers diverse products that provide both subsistence and commercial value, improving livelihoods and offering savings for further adaptation investments. *R. prinoides*-based agroforestry outperforms mono-cropping systems in terms of yield, income, and resilience to climate shocks, supporting adaptation strategies. These suggests the potential of scaling up tree-based farming to adapt climate impacts by maximizing and stabilizing production and income in the drylands where moisture stress is a major constraint of production.

R. prinoides-based agroforestry contributes to climate change mitigation through carbon sequestration, with significantly higher biomass and soil carbon stocks than annual crop mono-cropping. The biomass carbon stock (13.82 Mg ha^{-1}) and soil organic carbon (121 Mg ha^{-1}) in *R. prinoides* agroforestry are comparable to estimates from Matocha et al. (2012) and Mbow et al. (2014), indicating the potential of scaling up agroforestry to enhance carbon stocks in agricultural landscapes. To accurately estimate biomass and carbon stocks, the study developed a site- and species-specific allometric model for *R. prinoides*. It performed with less bias than general models aligning with Feyisa et al. (2016) and Yuen et al. (2016) arguments, demonstrating the importance of localized models for precise biomass estimation.

The significant role of *R. prinoides* agroforestry in climate change adaptation and mitigation highlights the need for locally tailored solutions, integrating indigenous knowledge and practices that align with local agroecological and socioeconomic contexts. Such bottom-up approaches can empower communities and facilitate the widespread adoption of sustainable, climate-smart farming practices.

8.2 Recommendations

The role of locally practiced tree-based farming in climate-smart agriculture, particularly in dryland areas, remains underexplored despite its potential to provide diverse products and ecosystem services. Research and development efforts should focus on assessing the characteristics, distribution potential, and climate adaptation and mitigation roles of indigenous tree/shrub-based farming systems. These systems can enhance productivity, resilience to climate variability, and carbon sequestration, making them key to achieving sustainable agricultural development.

Given that locally practiced agroforestry systems like *R. prinoides* have shown superior performance in climate resilience and carbon storage compared to specialized, annual crop mono-crop systems, scaling up tree-based farming should be prioritized in climate-smart agricultural strategies. Integrating trees and shrubs into farming systems can offer critical benefits in terms of improved productivity, diversified income streams, and enhanced climate resilience.

To effectively scale up tree-based farming systems, it is essential to design them based on a combination of indigenous knowledge, scientific research, and local context. Key considerations should include selecting appropriate tree/shrub species, optimizing spatial and temporal arrangements, and implementing proper cultivation and harvesting practices to maximize ecological and socioeconomic benefits. A tailored, context-specific approach is crucial for ensuring the sustainability and effectiveness of these systems.

Land use planning should be guided by agroecological and socioeconomic suitability assessments that consider climate change scenarios. For example, tree-based farming could be particularly beneficial in the midland and highland regions of Tigray, where it could support sustainable intensification and boost smallholder incomes.

Moreover, addressing market volatility for non-food commercial products, such as *R. prinoides* products, is critical for ensuring the sustainability of these systems. Developing predictable market access and price stability mechanisms will help smallholders integrate tree-based farming into their livelihoods more effectively.

Smallholders should be given a thorough assessment of farming practices to make informed decisions on alternative land uses. This is because farming systems that provide greater economic return and financial advantages could motivate sustainable land management strategies to achieve socioeconomic and environmental benefits.

Additionally, land tenure security, access to employment opportunities, and the potential for economic diversification should be key considerations when selecting tree-based farming systems. Ensuring that these systems are equitable, especially in empowering women economically, can drive broader societal benefits, contributing to more inclusive and sustainable agricultural development.

Finally, a bottom-up planning approach is essential to fully understand local conditions and challenges, ensuring the development of farming systems that are both agroecologically and socioeconomically viable. By leveraging indigenous knowledge and participatory decision-making, smallholders can adopt and scale tree-based farming practices that contribute to climate-smart agriculture and sustainable land management.

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Course Summery

Course code	Course title	Credit in ECTS	Completion date	Verification source
CCRD7111	Scientific inquiry	9	January 2018	Dept of Agricultural & Resources Economics, MU
CCRD7411	Scientific research writing	12	February 2018	Dept of Agricultural & Resources Economics, MU
CCRD7311	Environment, climate change and development	12	February 2018	Dept of Agricultural & Resources Economics, MU
CCRD7211	Contemporary issues in rural development	9	February 2018	Dept of Agricultural & Resources Economics, MU
CCRD7412	PhD Research Proposal Development & Defense	9	September 2018	Dept of Agricultural & Resources Economics, MU
CCRD7413	Thematic Seminars I	1.5	July 2022	Dept of Agricultural & Resources Economics, MU
CCRD7415	Thematic Seminars II	1.5	December 2023	Dept of Agricultural & Resources Economics, MU
CCRD7415	Thematic Seminars III	2	September 2024	Dept of Agricultural & Resources Economics, MU
CCRD7416	Paper presentation-National Conference	2	October 2020	ICS conference book of abstract, ICS letter of appreciation
CCRD7417	Paper Presentation-International Conference	2	March 2024	IKSAD conference call, paper presented, certificate of appreciation
CCRD7511	Dissertation	180	February 2025	Dept of Agricultural & Resources Economics, MU
Total		**240**		

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Summary

Destaalem Gebremeskel is a PhD candidate at Mekelle University, Department of Agricultural and Resources Economics in “Climate Change and Rural Development” program. Destaalem received a BSc degree in ‘Natural Resources Management’ from Hawassa University, Wondo Genet College of Forestry and Natural Resources, Ethiopia and an MSc degree in ‘Agricultural Development and Agroforestry’ from Copenhagen University, Denmark and Bangor University, UK. Destaalem has over 16 years work experience at Mekelle University, involved in many academic and research activities during his stay.

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ADDITIONAL INFORMATION

Publications

1. Gebremeskel D, Birhane E, Tesfay G, Tesfay A, Rannestad MM (2024) Assessing the socioecological benefits of *Rhamnus prinoides*-based agroforestry practice to smallholders in Tigray, Ethiopia. Socio-Ecological Practice Research, https://doi.org/10.1007/s42532-024-00195-9
2. Tesfay A, Birhane E, Gebremeskel D, Meressa AM, Rannestad MM (2024) Financial returns of Rhamnus prinoides based agroforestry practice in Tigray, Ethiopia. Agroforest Syst 98:679–696 https://doi.org/10.1007/s10457-023-00939-8
3. Gebremeskel D, Birhane E, Rannestad MM, Gebre S, Tesfay G (2021) Biomass and soil carbon stocks of *R. prinoides* based agroforestry practice with varied density in the dry-lands of Northern Ethiopia. *Agroforest syst*
4. Sakai T, Birhane E, Buruh Abebe B, Gebremeskel D (2021) Applicability of Structure-from-Motion Photogrammetry on Forest Measurement in the Northern Ethiopian Highlands. *Sustainability*, 13.
5. Gebremeskel D, Abebe B, Gidey K, Berihu T (2017) Effect of *Rhamnus prinoide* (Gesho) intercropping in wheat field on Soil nutrient and moisture in the drylands of North Ethiopia. *Momona Ethiopian Journal of Science, 9(2)*
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